Intergovernmental Oceanographic Commission
Workshop report no. 11 - Supplement

Collected contributions of invited lecturers and authors to the IOC/FAO/UNEP International Workshop on Marine Pollution in the Caribbean and Adjacent Regions

Port-of-Spain, Trinidad and Tobago,
13-17 December 1976

Unesco

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INTRODUCTION

The International Workshop on Marine Pollution in the Caribbean and Adjacent Regions was held in Port-of-Spain, Trinidad & Tobago, from 13 to 17 December 1976 under the sponsorship of the Intergovernmental Oceanographic Commission, the Food and Agriculture Organization of the United Nations (through its Western Central Atlantic Fishery Commission), and the United Nations Environment Programme.

Eight invited lectures were given at the Workshop so as to provide a common framework for discussion amongst the participants, who were mainly, but not entirely, scientists actively studying marine pollution problems in the region. The marine science infrastructure in the Caribbean region is not yet strong and it was not possible to ensure the participation of marine pollution experts from all the countries of the region. In some cases technical people concerned indirectly with marine pollution, particularly fishery experts, were invited.

The report of the Workshop (IOC Workshop report no.11) has been published separately and previously, in response to a request from the participants that it should be issued as soon as possible. At the same time, the participants wished to have the texts (or extended abstracts) of the eight lectures, as well as those of two information papers, also published. Since this would have delayed the publication of the report, the texts of the lectures and information papers have been published in the present supplement.

All invited participants, including the lecturers, took part in the Workshop in their individual capacity as experts in marine pollution or related fields.

In collecting these information papers and lectures in a supplement, some editorial changes have been made to provide a greater degree of uniformity of style and presentation, and to take account of the fact that they were prepared several months ago, before the Workshop, but are now being published after the Workshop.

PRELIMINARY REVIEW OF PROBLEMS OF MARINE POLLUTION IN THE CARIBBEAN AND ADJACENT REGIONS

This information paper was prepared by FAO. IOC/FAO marine pollution questionnaires answered by Member States were the main source of information for this paper.

CONTENTS

1. Introduction

The International Co-ordination Group (ICG) for the Co-operative Investigations of the Caribbean and Adjacent Regions (CICAR) at its sixth session in Cartagena, Colombia, in 1973 noted the increasing concern about marine pollution matters in the CICAR area. The meeting therefore recommended that FAO and IOC immediately take the necessary steps to obtain from countries in the CICAR area the basic information needed to hold a workshop on marine pollution.

A questionnaire on marine pollution in the Caribbean region was sent out by IOC in April 1974 to member countries of CICAR and by FAO to member countries of FAO not members of CICAR, and the Operations Co-ordinator of CICAR visited the CICAR member countries to obtain additional information on marine pollution in the region.

At the seventh session of the ICG for CICAR (Mexico, April 1975), it was recognized that the response to the questionnaires, so far, was unsatisfactory. Nevertheless, the CICAR National Co-ordinators were of the opinion that there existed a distinct urgency regarding marine pollution problems in the CICAR area, and therefore recommended that the Workshop on marine pollution be convened in 1976. A Steering Committee was established to organize the "International Workshop on Marine Pollution in the Caribbean and Adjacent Regions"; the Committee first met in Trinidad in October 1975.

The Western Central Atlantic Fishery Commission (WECAFC) of FAO recognized at its first session in Trinidad (October 1975) the importance of this Workshop, and agreed that it should be a joint WECAFC/CICAR effort. The United Nations Environment Programme (UNEP) agreed to co-sponsor and financially support the Workshop, and the Government of Trinidad and Tobago generously offered to host it.

The present report is a preliminary one. Originally it was intended to prepare a more complete review of the state of marine pollution, as was done for the two international workshops on marine pollution that were organized by IOC, FAO and UNEP for the Mediterranean Sea (Monaco, September 1974) and East Asian Waters (Penang, Malaysia, April 1976).

However, the scarcity of information on pollution problems in many countries of the region, which was reflected in the replies to the questionnaires, did not allow such an extensive review to be prepared in advance of the Workshop. This preliminary review therefore only provides some background information for the deliberations at the Workshop which will identify the main pollutants and the most urgent problems to be solved through regional co-operation. It is hoped that the experts who participated in the Workshop will complete as much as possible the information on the pollution problems in their respective countries so that a "Review on the State of Marine Pollution in the Caribbean and Adjacent Regions" can be prepared at a later date to assist in any action to follow up the Workshop.

The information contained in this preliminary report was received from:

(i) Replies to the questionnaire on marine pollution from the following CICAR and FAO member countries: Bahamas, Belize, Colombia, Cuba, Guatemala, Jamaica, Mexico, Nicaragua, Panama, Trinidad and Tobago, and the United States.

(ii) Papers presented at the FAO Technical Conference on Marine Pollution and its Effects on Living Resources and Fishing. Rome, 9-18 December 1970.

(iii) United Nations and FAO publications; e.g., UN Statistical Yearbook 1974, FAO Production Yearbook 1974.

(iv) Papers presented by Colombian, Cuban and Mexican participants at various FAO/SIDA Training Courses on Marine Pollution concerning pollution problems in their respective countries.

The present paper was prepared by Mr A. Wenblad, FAO Technical Secretary of the Workshop, and Dr G. Tomczak, FAO Fishery Resources and Environment Division (Chapter 1).

2. Description of the Region and Some Hydrographic Aspects

2.1 Introduction

The area under consideration for the purpose of the Workshop encompasses the Caribbean Sea and the Gulf of Mexico and is bordered on the north, west and south by the American continent and on the east by the islands of the Greater and Lesser Antilles.

The total area of this region is 4.31×10^6 km^2. As the mean water depth is 2,174 m., the total volume of the water masses in the region is 9.37×10^6 km^3. The greatest water depth is found in the Cayman trench (6,895 m) to the west of Jamaica.

The Caribbean Sea can be subdivided into various basins which are bordered by submarine sills. Thus, a sill of mostly less than 200 m between Jamaica and Honduras separates the Yucatan Basin in the north of the Caribbean Sea from the main part of this sea; several sills with depths of less than 3,000 m also divide this main body of the Caribbean Sea into three different basins: the Colombian Basin in the west, the Venezuelan Basin in the middle of the area, and the small Grenada Basin to the west of the Leeward and Windward Islands.

The following general description of some hydrographic features that may affect the distribution and movement of pollutants may help in understanding the relationship between the state of pollution in coastal areas and in the open sea. More detailed papers on the hydrography of

the region and on the various dispersion processes follow the present one. In the light of the findings of CICAR a co-operative study of the Caribbean area designed to provide a more detailed knowledge of surface and deep-water circulation, renewal of water masses in the deep basins, seasonal variations of temperature and salinity, especially as regards upwelling areas, effects of river outflow, etc., and their relation to pollutant distribution, should be carried out.

2.2 Surface-water circulation

The most striking hydrographic feature in the region is the continuous flow of water through the area from east to west in the Caribbean Sea proper, followed by a movement from southeast to northeast in the Yucatan Basin, and finally, in the Gulf of Mexico, a strong flow to the east again through the Straits of Florida, after an anticyclonic movement of most of this water in the western area of the Gulf.

Approximately 30×10^6 cubic metres of water per second pass through the various passages between the islands of the Lesser Antilles transported to them by the combined equatorial currents. The general movement of this water, which is stable all the year round although some seasonal changes can be found in the velocities, is shown schematically in Figure 1 in which an area of continuous flow is indicated by a dotted line. The velocities given are mean velocities during the year. Seasonal changes can be expected, however, and much higher velocities will be found, especially where the water is forced through narrow passages, such as the Yucatan Channel or the Straits of Florida; velocities up to 3.5 and 4.5 kn, respectively, are observed in the current core in these two areas.

Outside the dotted line currents are weaker and also unstable. During some months, large vortices are formed off the coast of Costa Rica, Panama and Colombia, and similarly in some parts of the Gulf of Mexico. The main circulation in the latter, as already pointed out, forms an anticyclonic movement flowing through the western part of the area and, eventually, combining its flow in the Straits of Florida with the water masses which turn after passage through the Yucatan Channel immediately to the east, the latter movement being more pronounced during the northern hemisphere winter months.

2.3 Sea-surface temperature: areas of upwelling

The surface temperature in the tropical parts of the region has an average value of about 27°C and does not vary considerably during the year. The seasonal fluctuations do not exceed 3°C. This is also true for the southernmost part of the Gulf of Mexico. However, its northern part shows extreme seasonal changes in temperature, from about 16°C in winter time to 28°C in the summer, so that during the winter months there is a strong latitudinal temperature gradient.

The cooling of surface waters in the northern and central part of the Gulf of Mexico during winter months also affects the vertical temperature

distribution. Whereas in the whole Caribbean area and adjacent seas the temperature decreases by 10-15°C during the first 200 m, beyond which depth there is only very slow further decrease, a thermocline layer is formed during the winter in parts of the Gulf of Mexico at depths that may sometimes reach 100 m.

Although this will have some influence on the mixture of any potential pollutant in the area, more important in this connection seems to be the development of upwelling which takes place particularly along the north coast of the Yucatan Peninsula from May to October, with a peak in June, and off the northeastern Venezuelan coast where upwelling is strongest between December and April.

3. Sources and Effects of Pollution

3.1 Introduction

The following sections give primarily a summary of the replies to the questionnaires on pollution in the Caribbean. Due to lack of the information available in some countries, several of the replies are rather incomplete while some give quite adequate information. For this reason the countries may be divided into three groups:

(i) Sufficient information: Mexico and the United States.

(ii) Limited information: Colombia, Cuba, Jamaica, Trinidad and Tobago.

(iii) Little information: The Bahamas, Belize, Guatemala, Nicaragua, Panama.

An effort has been made to include additional information to permit some estimation of the major pollutants and of the kind of pollution problems that can be expected. General demographic and geographic data, as well as data on major industrial and other activities that may be a source of pollution, have therefore been included. It must be pointed out, however, that only direct studies, as part of national monitoring programmes, can establish the extent of coastal pollution from these sources.

To give an estimation of the organic load from the domestic sewage, the following figures have been used:

Biochemical oxygen demand (5 days), BOD_5 = 20 kg per person per year

Phosphorus content : 0.9 kg P per person per year

These figures are the same as those used by the General Fisheries Council for the Mediterranean (GFCM) in a review of the state of marine pollution in the Mediterranean (GFCM Studies and Reviews No.51, 1972).

Pollution originating from oil-processing industries can be quite considerable especially around big oil refineries. In order to give an estimate of this pollution it can be assumed that about 1 m^3 of water is used for each ton of crude oil processed in the refinery (excluding water for cooling purposes) and that the resulting effluents contain amounts of oily substances in concentrations of about 100 ppm. A refinery with a capacity of 10 million tons per year may then release 1,000 tons of oil per year.

3.2 Mexico

Mexico has an area of 1,969,269 km^2 and a coastline along the Gulf of Mexico of 2,611 km. The population is about 58 million (1974). Mexico's nominal fish catch in the western central Atlantic is reported to be 124,650 tons (1974).

Main rivers:

(i) Grande-Bravo del Norte, total length 2,890 km, catchment area 442,900 km^2. The frontier between Mexico and the United States runs along the river for 1,600 km.

(ii) Panuco, total length is 450 km.

(iii) Papaloapan, total length is approximately 540 km.

(iv) Grijalva

Among the main industries are:

fisheries, food-processing, breweries, distilleries, tanneries, textiles, mining and metallurgy, pulp and paper, shipyards, fertilizers, crude-oil production, oil refineries, petrochemicals, chemicals and pharmaceuticals.

Domestic pollution, including bacteriological contamination, is considered a problem especially for the production of crustaceans. The contaminated organisms, oysters, mussels and some fish, for example, may be rendered unsuitable for human consumption and may also show an increased mortality. This situation occurs commonly in areas where there is a continuous discharge of untreated domestic sewage.

Industrial pollution :

Grande-Bravo del Norte area

Breweries and distilleries: organic material, ethyl alcohol, detergents and caustic soda.

Oil refineries: crude oil, lead compounds, surface-active agents, phenols, acids and alkalis.

Petrochemical industry: petroleum derivates, benzene, ethylbenzene, toluene, acetaldehyde, heavy aromatics, dodecylbenzene and several other derivatives.

Monterrey area

Food industry: organic material, detergent, caustic soda.

Pharmaceutical and chemical industry: various chemical compounds.

Tanneries: organic material, tannic acid, chromium salts.

Metallurgical industry: cooling oils, acidic and alkaline deoxidizing solutions, metal oxides, cyanide and various metal salts.

Pulp and paper industry: debarking waste, cooking liquors, wood and paper fibres, various chemical substances: e.g., arsenic compounds, sulphate liquors, lignin compounds, carbohydrates.

Textile industry: wood and cotton fibres, colouring compounds.

Mining: sulphuric acid, salts of various metals (e.g., copper, lead, zinc), ash, sand.

Pesticide industry: residues of DDT, aldrin, endrin, lindane, etc.

Panuco area

Food industry, sugar industry: organic material, bleaching residues: hypochlorites and calcium oxide, detergents and caustic soda.

Pharmaceutical and chemical industry, pulp and paper industry, oil refineries, petrochemical industry, and mining.

Nueva Faja de Oro

Crude oil production and oil refineries.

Papaloapan area

Breweries and distilleries, sugar industry, pharmaceutical and chemical industry, tanneries, pulp and paper industry, textile industry.

Grijalva area

Food industry, sugar industry and petrochemical industry.

Isla del Carmen

Food industry.

Merida area

Breweries and distilleries, food industry, wood-preserving industry: organic material, creosote oil.

The effects of industrial pollution on the coastal waters have been indicated as moderate from Tampico to Veracruz, and severe from Veracruz to Tabasco.

Pesticides: Among the pesticides that are in use, quantities are given for agricultural use of the following (1972):

Aldrin	837 tons
Endrin	13,667 tons
Dieldrin	Varying
Lindane	58 tons
DDT	1,325 tons

3.3 United States

The Gulf of Mexico is bordered by the following States:

Florida	population :	6.8 million	area :	135,000 km^2
Alabama	population :	3.4 million	area :	125,000 km^2
Mississippi	population :	2.2 million	area :	118,000 km^2
Louisiana	population :	3.6 million	area :	112,000 km^2
Texas	population :	11.2 million	area :	653,000 km^2

Of the total population of 27.2 million, about 6.5 million are living in the coastal counties. The population of the coastal urban areas is about 3.5 million.

Main rivers:

The contributing river basins from the south of Florida to the Mexican border are listed in Table 1. The Gulf of Mexico has been divided into nine parts where the drainage areas and the total discharge are listed. Major rivers are listed under "Discharge from selected river basins". Of the total discharge of 25,120 $m^3\ sec^{-1}$, 18,400 come from the Mississippi River.

The total suspended load due to sedimentation in the whole of the Gulf of Mexico is about 360 million tons per year.

Table 1

Discharge of Rivers to the Gulf of Mexicc

Contributing basin	Drainage area	Total discharge	Discharge from selected river basin
	km^2	$m^3 sec^{-1}$	$m^3 sec^{-1}$
1. Cape Sable to Alligator Creek		71	
2. Peace River to New River	67,600	770	
River basin: Suwanee River			302
3. Apalachicola River	51,800	756	
4. Wetappo Creek to Perdido River	36,800	711	
River basin: Choctawhatchee River			208
Escambia River			195
5. Mobile Bay	114,700	1,818	
River basin: Mobile River			1,788
6. Pascagoula River to Pearl River	51,000	883	
River basin: Pascagoula River			430
Pearl River			365
7. Mississippi River	3,220,900	18,400	
8. Vermilion, Mermentau and Calcasieu Rivers	22,500	306	
9. Sabine River to Rio Grande	875,900	1,407	
River basin: Sabine River			256
Neches River			233
Trinity River			212
Brazos River			176
Colorado River			85
Guadalupe and San Antonio Rivers			67
Nucces River			23
Rio Grande			19
Rounded totals :		25,120	

Domestic pollution:

Coastal municipal waste discharge for each State is listed in Table 2. Discharges from Florida coastal counties into both the Gulf of Mexico and the Atlantic Ocean have been included.

There are some difficulties in calculating the organic load from this discharge since the efficiency of the treatment is not given. To give an approximate amount, the figure of 20 kg BOD_5 per person per year is used as previously. Minor and primary treatment is estimated to reduce BOD by 30 per cent whereas secondary and tertiary treatment may reduce BOD by as much as 80 per cent. The total organic load from coastal municipal waste would then be about 35,000 tons BOD_5 per year. In addition domestic sewage will enter the coastal waters with the rivers but the information is not sufficient to make a calculation of this load.

Industrial pollution:

Table 3 gives a summary of the coastal industrial waste discharge. The figures are for years up to 1970. The data indicate the importance of various manufacturing industries in the different States, and mainly relate to industrial activities in the coastal counties but do not include all industrial waste water carried with the main rivers.

In addition to discharge from land-based sources, about 13 million tons of dredging spoils and 700,000 tons of industrial waste are dumped into the Gulf of Mexico per year (1968).

The coasts of Texas and Louisiana are very important producers of petroleum, and the oil-well drilling platforms are numerous in the near-shore waters. Little information is available on the extent of pollution from oil production in the Gulf of Mexico. (A lecture on petroleum pollution of the Gulf of Mexico is reproduced later, however; see page 146.)

Pesticides:

Nearly 100 companies in the United States produce active pesticidal ingredients. Data on the production of these pesticides are virtually unavailable on an individual compound basis. Table 4 gives a summary of production volumes of selected herbicides, insecticides and fungicides (data refer to 1972).

As the Mississippi River system drains 41 per cent of the land area of the United States, including much of the agricultural heart-land, the pesticides and fertilizers draining from it flow into the Mississippi River and may contribute considerably to the pesticide load in the Gulf of Mexico. Fish kills in the Mississippi River and damage to marine resources have been traced to excessive pesticide concentrations.

Table 2

Coastal Municipal Waste Discharge Summary

	Type of treatment	Number of discharges	Population served x 1,000	Average daily flow, million gallons per day
FLORIDA	None	0	0.00	0.00
	Minor	2	70.00	7.00
	Primary	34	447.02	61.01
	Intermediate	0	0.00	0.00
	Secondary	371	2,581.57	247.62
	Tertiary	3	4.02	0.26
	Total	410	3,102.62	315.89
ALABAMA	None	0	0.00	0.00
	Minor	0	0.00	0.00
	Primary	2	35.20	2.65
	Intermediate	0	0.00	0.00
	Secondary	15	207.56	23.61
	Tertiary	0	0.00	0.00
	Total	17	242.76	26.26
MISSISSIPPI	None	0	0.00	0.00
	Minor	0	0.00	0.00
	Primary	0	0.00	0.00
	Intermediate	0	0.00	0.00
	Secondary	8	151.00	14.59
	Tertiary	0	0.00	0.00
	Total	8	151.00	14.59
LOUISIANA	None	1	15.00	1.50
	Minor	0	0.00	0.00
	Primary	2	453.00	26.30
	Intermediate	0	0.00	0.00
	Secondary	49	444.73	45.33
	Tertiary	0	0.00	0.00
	Total	52	912.73	73.13
TEXAS	None	0	0.00	0.00
	Minor	0	0.00	0.00
	Primary	3	12.50	0.43
	Intermediate	0	0.00	0.00
	Secondary	197	2,032.62	136.67
	Tertiary	1	1.70	0.00
	Total	201	2,046.82	137.10
TOTAL	None	1	15.00	1.50
	Minor	2	70.00	7.00
	Primary	41	947.72	90.39
	Intermediate	0	0.00	0.00
	Secondary	640	5,417.48	467.82
	Tertiary	4	5.72	0.00

Table 3

Coastal Industrial Waste Discharge Summary
Water Discharged in 1970, million gallons per day

State	Food Products	Pulp and paper	Chemical	Petroleum	Primary metals	Total
FLORIDA						
Discharged to:						
Public sewers	2.43	0.00	0.22	0.00	0.00	2.65
Surface water	36.64	175.66	69.86	0.00	0.00	282.16
Tidewater	2.59	190.57	106.02	0.00	0.00	299.18
Ground	3.52	1.94	1.08	0.00	0.00	6.53
Total	45.17	368.14	177.17	0.00	0.00	590.49
Treated	6.70	179.28	65.95	0.00	0.00	251.91
ALABAMA						
Discharged to:						
Public sewers	0.10	0.18	0.53	0.00	0.00	0.82
Surface water	0.10	239.74	58.00	0.00	0.00	297.84
Tidewater	0.29	69.47	1.75	0.00	0.00	71.51
Ground	0.05	2.35	0.30	0.00	0.00	2.69
Total	0.54	311.73	60.59	0.00	0.00	372.86
Treated	0.05	201.31	8.32	0.00	0.00	209.68
MISSISSIPPI						
Discharged to:						
Public sewers	0.00	0.00	0.13	0.00	0.00	0.13
Surface water	0.00	0.00	6.66	0.00	0.00	6.66
Tidewater	0.00	0.00	0.88	0.00	0.00	0.88
Ground	0.00	0.00	0.06	0.00	0.00	0.06
Total	0.00	0.00	7.72	0.00	0.00	7.72
Treated	0.00	0.00	1.35	0.00	0.00	1.35
LOUISIANA						
Discharged to:						
Public sewers	6.68	0.01	0.13	0.00	0.00	6.82
Surface water	56.03	0.38	154.71	72.66	0.00	283.77
Tidewater	10.63	0.00	20.16	26.83	0.00	57.60
Ground	11.87	0.00	0.71	1.68	0.00	14.26
Total	85.22	0.38	175.70	101.16	0.00	362.47
Treated	16.14	0.30	15.07	64.60	0.00	96.12
TEXAS						
Discharged to:						
Public sewers	5.62	1.00	4.90	0.88	0.25	12.69
Surface water	4.32	42.61	66.89	335.50	28.55	477.86
Tidewater	10.03	51.04	3,318.60	169.12	352.68	3,901.47
Ground	0.60	0.00	5.14	4.42	0.09	10.14
Total	20.64	94.65	3,395.53	509.75	381.55	4,402.15
Treated	1.47	69.12	159.01	423.51	13.27	666.38
TOTAL						
Discharged to:						
Public sewers	14.83	1.19	5.91	0.88	0.25	23.11
Surface water	97.09	458.39	356.12	408.16	28.55	1,348.29
Tidewater	23.54	311.08	3,347.41	195.95	352.68	4,330.64
Ground	16.04	4.29	7.29	5.92	0.09	33.68
Total	151.57	774.91	3,816.74	610.91	381.55	5,735.69
Treated	24.36	450.01	249.69	488.11	13.27	1,225.44

Table 4

Summary of Production Volumes of Selected Herbicides, Insecticides and Fungicides

Pesticide group	Number of products by production volume ranges (million pounds)						Total no. of specified products	Production volume (million pounds)		
	45	45-25	25-10	10-5	5-1	1		Specified products	Unspecified products	All products
Herbicides [a/]	1	4	4	11	17	22	59	423	5	428
Insecticides [b/]	3	3	4	6	15	25	58	393	10	403
Funcigides [c/]	0	2	2	0	5	9	18	143	2	145
Total	4	9	10	17	37	56	135	959	17	976

a/ Including defoliants and plant growth regulators.

b/ Including organic, inorganic and biological insecticides; excluding attractants, repellents, synergists; rodenticides, molluscicides, fumigants and soil conditioners.

c/ Considering the dithiocarbamate as a single product, and counting pentachlorophenol as primarily a fungicide, but excluding sulphur, inorganic copper and other salts.

3.4 Colombia

Colombia has an area of 1,138,300 km^2 with a coastline in the Caribbean of 1,560 km. The population is 22.9 million (1972).

The main fisheries are in the Pacific but the fish catch in the western central Atlantic is about 13,400 tons (1974).

Main rivers:

(i) Magdalena, total length 1,550 km, catchment area: 200,000 km^2. Examples of chemical data from the lower part of the river (Ducharme, 1975): pH 7.65-8.1; Turbidity JTU: 215-500; Conductivity S: 225; NO_3 ppm: 4.0-22.0; PO_4 ppm: 0.18-0.37; Cu ppm: 0.02

(ii) Sinu, total length 400 km. Examples of chemical data (Ducharme, 1975): pH: 7.1-9.1; Turbidity JTU: 100-500; NO_3 ppm: 0.15-3.0; PO_4 ppm: 0.2-1.5; Cu ppm: 0.3-3.6

(iii) Atrato, total length 600 km.

The main industries are: textiles, food-processing, crude oil production, oil refineries, petrochemicals and chemicals, wood, mining and metallurgy. The annual (1973) production of crude oil is 9.5 million m^3 and the refinery capacity is 8.1 million tons.

Domestic pollution occurs mainly around the capital cities along the coast; of these, Baranquilla (700,000 inhabitants), Cartagena (350,000 inhabitants) and Santa Marta (200,000 inhabitants) are the largest. Sewage is apparently released without treatment. Domestic pollutants can also be expected to be carried out with the main rivers entering the Caribbean. The organic load from the three largest cities would be approximately 25,000 tons BOD_5 per year and 1,100 tons of phosphorus per year.

Due to domestic pollution, depletion of shrimp and lobster resources has been reported in the Bay of Taganga.

The industrial activity is very diversified, as mentioned above, and, therefore, a wide variety of industrial pollutants can be expected to enter the sea.

Fishery industries, as well as other food-processing industries, are reported to cause bacteriological pollution in the Bay of Tanganga.

Other industrial activities that may cause organic pollution are wood-processing industries and distilleries.

Among chemical and metallurgic industries can be mentioned: shipyards, petrochemical industry, DDT manufacture, fungicide manufacture, fertilizer manufacture and steel industry.

Various kinds of pesticides are used in agriculture but no information is available on their possible effects on living aquatic resources. Among the pesticides which are in use, the following quantities used in 1973 are given:

DDT	1,140 tons
Parathion	2,000 tons
Malathion	370 tons

3.5 Cuba

Cuba has an area of 114,524 km^2 with a coastline of about 4,000 km. The population is 8.9 million (1973) with approximately 1.8 million in La Habana.

Most rivers are short and run swiftly from the mountains to the sea; the main river, Canto, is 370 km long.

The Cuban fish catch (landed) in the western central Atlantic was 73,000 tons in 1974.

Among the main industrial activities can be mentioned: mining (nickel, cobalt and iron) and basic metal production (about 36,000 tons of nickel are produced per year), sugar refineries, distilleries, breweries, fisheries industry, pulp and paper industry, shipyards and fertilizer industry.

Domestic pollution occurs mainly around the major coastal cities, such as La Habana with its 1.8 million inhabitants. For the whole of Cuba, the organic load from domestic sewage can be estimated to be about 500 tons BOD_5 per day. However, it is impossible to estimate how much of this total load actually enters the coastal waters, as the rural communities are often served by septic tanks, and the rivers into which sewage is discharged have a certain self-purifying capacity.

The industrial activity is very diversified, as mentioned above, and, therefore, a wide variety of industrial pollutants may enter the sea.

From mining and metallurgy, nickel, copper, lead, iron and chromium have been indicated to be of significance.

Waste water from sugar refineries has a high BOD_5 concentration, about 5,000 mg l^{-1} on the average, and, therefore, contributes considerably

to the organic load in the receiving waters. Distilleries also have a very high BOD_5 content in the waste water which is also highly coloured.

Other industries that release waste water with a high organic load are breweries, fisheries industry and food-processing industries.

Although little information is available about the effects on aquatic organisms of these kinds of pollution, considering the high BOD load severe effects can be expected, at least locally, if no treatment is undertaken.

3.6 Jamaica

Jamaica has an area of 11,430 km^2 with a coastline of about 519 km. The population is about 2.0 million (1970).

Total annual Jamaican fish catch in the western central Atlantic is about 10,000 tons (1974).

Jamaica is the world's largest producer of bauxite and aluminia. Reserves of commercial grade bauxite have been estimated to be between 500 and 600 million tons and the bauxite production is about 13 million tons per year, half of which is locally processed into aluminia. Other main industrial activities are oil refineries, with a capacity of 1.6 million tons per year, and distilleries.

Domestic pollution:

The chief sources, Kingston and Montego Bay, as well as individual large hotels on the north coast, are indicated to have sewage treatment, but without knowing the type and efficiency of the treatment, the organic load cannot be estimated.

High bacteria concentrations, as well as frequent plankton blooms and fish kills, are reported from Kingston harbour.

Industrial pollution:

Waste waters from bauxite mining and aluminia production, as well as from the sugar industry and distilleries are discharged mainly to rivers, but can be expected to affect the coastal waters in the river mouths. It is also known from other countries that waste from aluminia production causes considerable pollution problems.

From the Kingston area there is a diversity of industrial effluents, and the effects on Kingston Bay have been indicated as strong.

In Portland Bight, Montego Bay and Ocho Rios, the effects of industrial waste waters have been indicated as moderate.

Fouling of boats, fishing gear, mangroves and beaches from oil pollution is reported from the Kingston area and Portland Bight.

Various pesticides (malathion, DDT, lindane, etc.) are used in agriculture and urban pest control.

3.7 Trinidad and Tobago

Trinidad and Tobago have a total area of 5,127 km^2 with a coastline of 470 km. The population is 1.1 million (1970) and 150,000 live in the capital, Port-of-Spain; the second largest town, San Fernando, has a population of 50,000 inhabitants.

Fish production from the western central Atlantic is 3,380 tons (1974).

The main industrial activities are oil production, including refineries, asphalt production, sugar mills, distilleries, breweries and a fertilizer factory.

Direct sewage discharge is mainly from Port-of-Spain and San Fernando. As it is indicated that the sewage is treated, the organic load is difficult to calculate without knowing the efficiency of the treatment, but can be estimated at 1,000-1,500 tons BOD_5 per year from Port-of-Spain and 300-500 tons BOD_5 per year from San Fernando, assuming 30-50 per cent BOD reduction in treatment.

The industrial effluents that cause pollution mainly come from petroleum refineries, distilleries and breweries. The crude oil production is 8.5 million m^3 per year (1973) but as crude oil from some other countries in the region is refined in Trinidad the refinery capacity is about 22.5 million tons.

The petroleum industry is located around San Fernando whereas the distilleries and breweries are in Port-of-Spain.

The effects of industrial waste water have been indicated as strong in the Gulf of Paria on the west coast while effects on the other coasts are negligible. Frequent fish kills have occurred in coastal lagoons.

Oil pollution also occurs on the east coast and is believed to come from bilge and tank-cleaning activities.

3.8 Bahamas

The Bahamas consist of about 300 islands with a total area of 13,722 km^2. Thirty islands are inhabited, the total population being about 180,000 (1972). Fish production from the western central Atlantic is 2,992 tons (1974).

The main industrial activities are: oil refineries (capacity: 24 million tons per year), petrochemical industries, oil terminals, rum distilleries, breweries and cement manufacturers.

Domestic pollution occurs mainly around the northern coast of New Providence where sewage from Nassau (100,000 inhabitants) is discharged without treatment. The organic load from this discharge would be about 2,000 tons BOD_5 per year. Bacteriological investigations have shown high E. coli concentrations. On the west coast of Grand Bahama Island untreated sewage is discharged from Freeport (30,000 inhabitants).

Effects of industrial pollution have, however, been indicated as strong on the northern coast of New Providence, as well as the west coast of Grand Bahama, where the oil refineries and oil loading terminals are located.

3.9 Belize

Belize has an area of 22,965 km^2 with 280 km of coastline. The population is 128,000 (1972) with approximately 40,000 living in Belize City.

The Belize river is the main river. Fish production is about 1,900 tons per year (1974). Extensive coral reefs are located off the coast.

Production is mainly related to forestry and agriculture, including some sugar mills.

Domestic pollution occurs mainly off Belize City where sewage is discharged without treatment; the effects are not, however, considered very significant. Seasonally high levels of pollution can occur from the sugar mills.

Pesticides are used in rice fields and eventually run off into the Belize river, but no information is available about effects on living aquatic resources.

3.10 Guatemala

Guatemala has an area of 108,889 km^2 with a coastline along the Caribbean of 110 km. The population is 5.3 million of which about 1 million live in Guatemala City.

The main river entering the Caribbean is the Motagua with a total length of about 400 km.

Industrial activity is mainly limited to light industry for local needs. Mining of nickel is of growing importance, and the large-scale exploitation of nickel deposits close to Lake Izabal has recently started.

Domestic pollution from the three towns (total population 70,000) on the Caribbean coast can be calculated as 1,400 tons BOD_5 and 60 tons of phosphorus per year.

Industrial pollution may be expected from the mineral exploitation and subsequent refining, especially at the nickel mines at Lake Izabal. No detailed information is available, however.

An oil spill occurred off the coast of Guatemala in April 1975 when a barge sank 5 km NNE of Punta de Manabique. An expert group was sent by FAO to study the affected areas and estimate the economic losses due to the oil spill. The financial losses due to interruption of fishing activities, as well as contamination of equipment, was estimated to be about U.S.$ 150,000.

3.11 Nicaragua

Nicaragua has an area of 139,699 km^2 with a coastline in the Caribbean of 450 km.

The population is about 1.9 million with the main part in the capital, Managua, and on the Pacific side of the country.

Main rivers:

(i) Grande de Matagalpa, total length 418 km

(ii) Coco, total length 433 km

Industrial activity on the Atlantic coast is mostly limited to some small fish-processing plants in Bluefields and elsewhere.

Domestic pollution is indicated as insignificant because of the small population on the Caribbean coast. The organic load from about 70,000 inhabitants can be calculated to be about 1,400 tons BOD_5 per year. This is, however, distributed over most of the coastline.

Pesticides are not used in the agricultural activities on the Caribbean coast.

3.12 Panama

Panama has an area of 75,835 km^2 and the population is about 1.5 million (1970).

The main industries are: oil refineries, sugar refineries, marble cutting and polishing, fisheries and shipyards.

Domestic pollution on the Caribbean coast mainly occurs around the canal zone where Colón (100,000 inhabitants) is the largest town. The organic load from Colón where sewage is released without treatment would

be about 2,000 tons of BOD_5 per year. The beaches around Colón are reported to be bacteriologically contaminated.

An oil refinery with a capacity of 3-4 million tons per year operates in Colón, and several incidents of release of oil are reported. Release of oil also occurs from the heavy ship traffic through the canal zone when bilge and ballast water is released. There is no control of this release.

The effects of industrial effluents in the area around Colón have in general been indicated as strong.

4. Summary

The pollution problems in the countries in the Caribbean and adjacent regions vary widely depending on the size, population, type of agricultural production and extent of industrialization in the various countries.

Some types of pollution such as organic pollution from domestic waste are however common problems for the whole region. Domestic waste problems are associated with all major cities in the area and will increase as urbanization continues. The development of sewage treatment facilities will not be able to keep up with population growth and as a result the assimilative capacities of natural waters will continue to be exceeded.

Organic wastes from sugar refineries, pulp and paper mills and the agricultural industry can also contribute considerably to the oxygen demand of the waste waters.

Metallurgic and other industries present a different type of pollution problem as the wastes usually contain a mixture of organic wastes and inorganic and organic chemical substances which must be treated in a more complex way. Table 5 indicates the metal mining production in the region. The extent of pollution problems from these types of industry varies considerably from country to country. Only national programmes to monitor various industries and receiving waters can establish the actual extent of pollution and indicate what counter measures are necessary.

Pesticide contamination will continue as agriculture expands. Pesticide residues in coastal marine resources may, however, decrease with the development and use of less persistent chemicals.

Oil exploration and exploitation are intensive in the Caribbean region, and the level of contamination is increasing due to the expansion of off-shore drilling. Apart from measures to prevent oil spills and tanker collisions, the protection of valuable coastal resources depends on the efficiency and speed of containment and recovery of oil spills at the source. These measures should, however, be carefully co-ordinated with the need for the protection of living resources, and pilot studies to estimate ecological damage by oil should be organized.

Table 5

Mining Production 1973 (thousand metric tons)

	Bauxite	Chromium ore (Cr_2O_3 content)	Copper ore (Cu content)	Lead ore (Pb content)	Manganese ore (Mn content)	Mercury ore(2)	Nickel ore(2)	Tin concentrates (Sn content) (2)	Zinc (Zn content)	Iron ore (Fe content)
Belize										
Bahamas										
Colombia						5				439
Costa Rica										
Cuba		13.0	5.0				36,789(3)			
Dominican Republic	1,411						30,100			
Guatemala				0.1						
Guyana	3,497									
Haiti	779		6.6(1)							
Honduras				18.5					19.7	
Jamaica	13,489									
Mexico			80.5	179.3	131.0	197	32	293	271.4	3,113
Nicaragua			1.5							
Panama										
Puerto Rico										
Trinidad and Tobago										
United States	2,324		1,558.5	547.1	23.4	75	17,445		434.4	53,236
Venezuela										14,179
Surinam	6,686									

Notes : (1) 1971
(2) metric tons
(3) 1972 content of oxide and sulphide

Source : UN Statistical Yearbook 1974

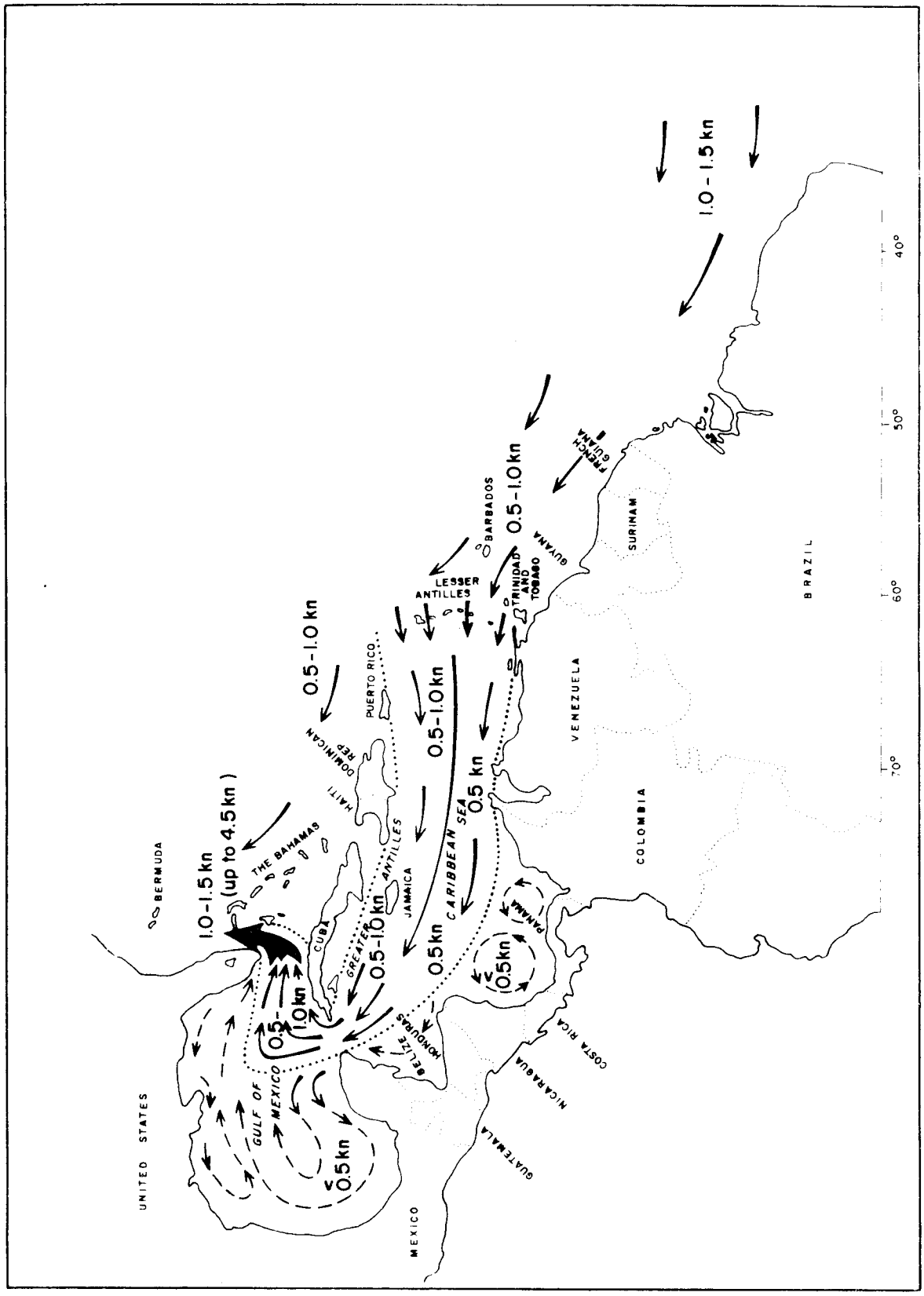

Fig. 1 General water movements

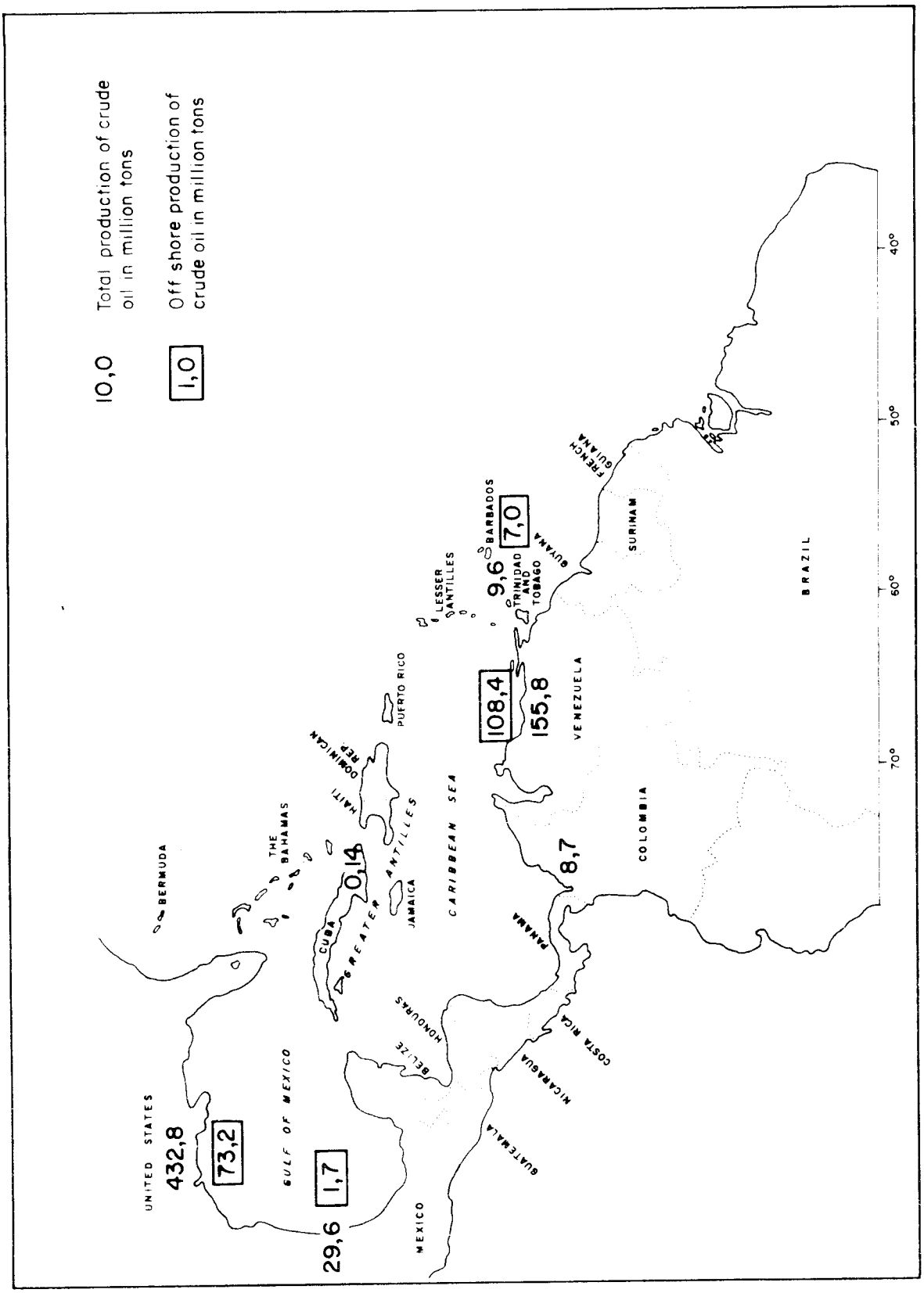

Fig. 2 Crude oil production 1974. (From: United Nations world energy supplies, 1950 - 1974)

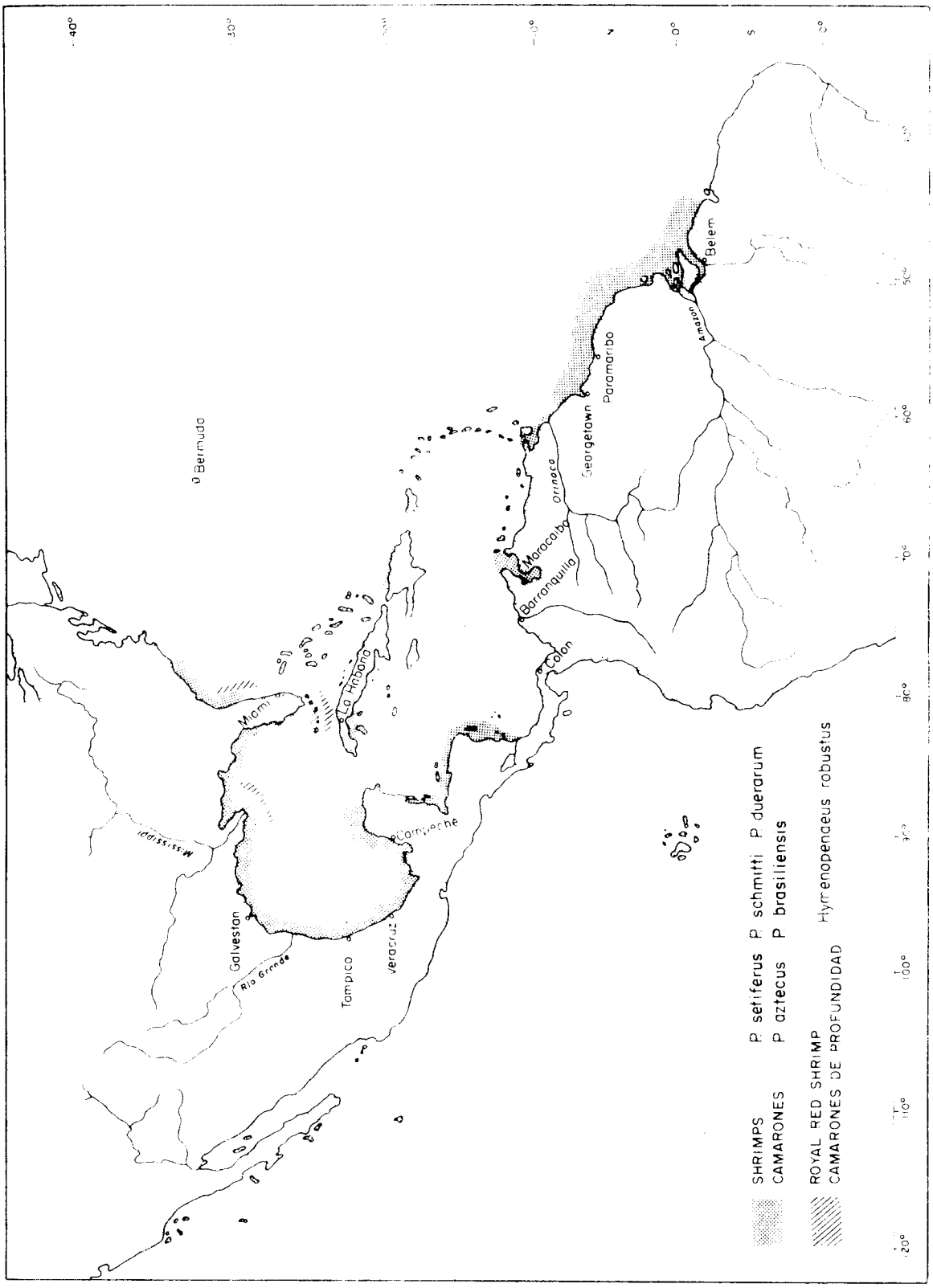

Fig. 3 West Central Atlantic crustacean resources. (From: FAO, Atlas of the Living Resources of the Sea, 1972)

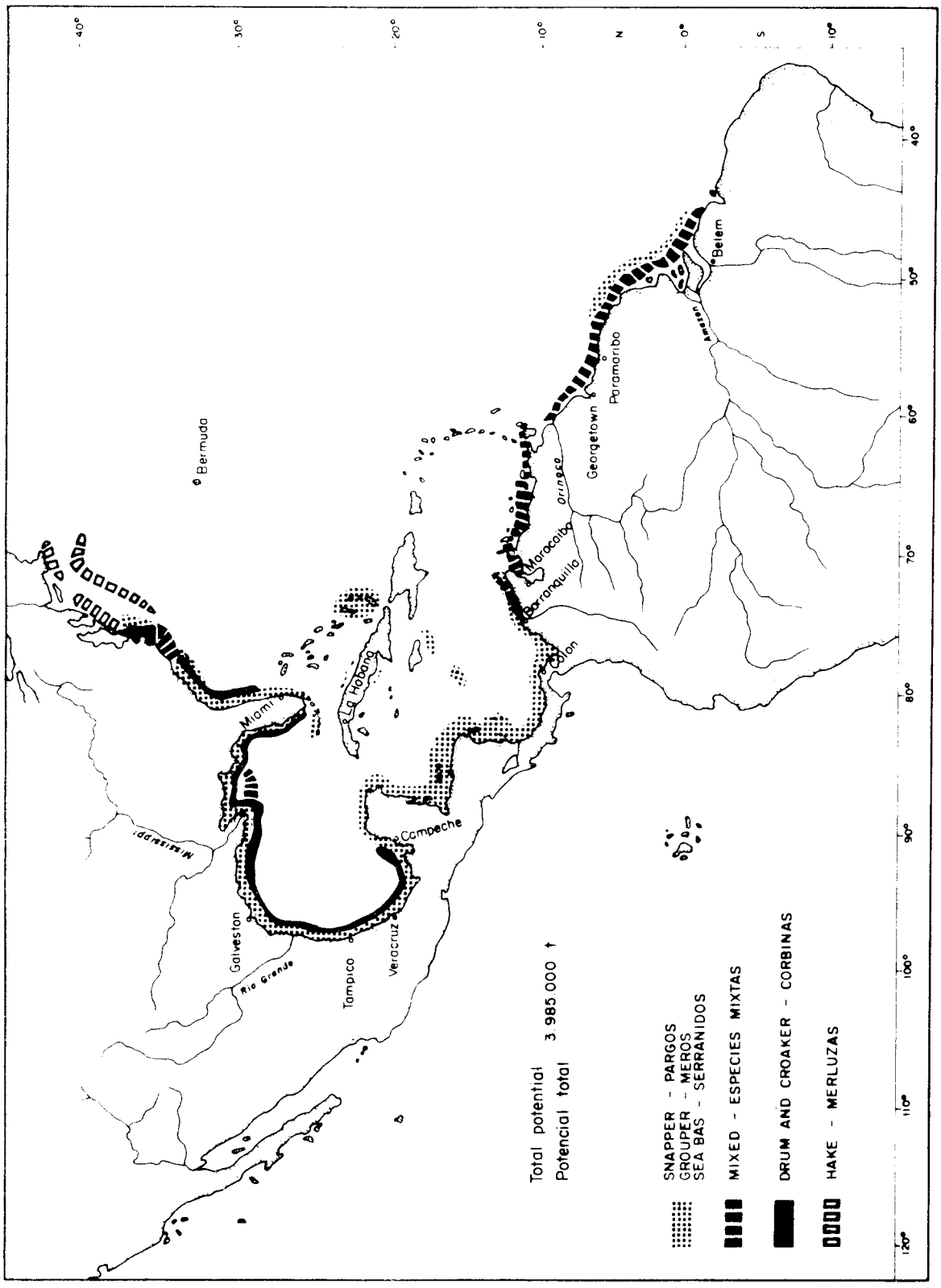

Fig. 4 West Central Atlantic demersal resources. (From: FAO, Atlas of Living Resources of the Sea, 1972)

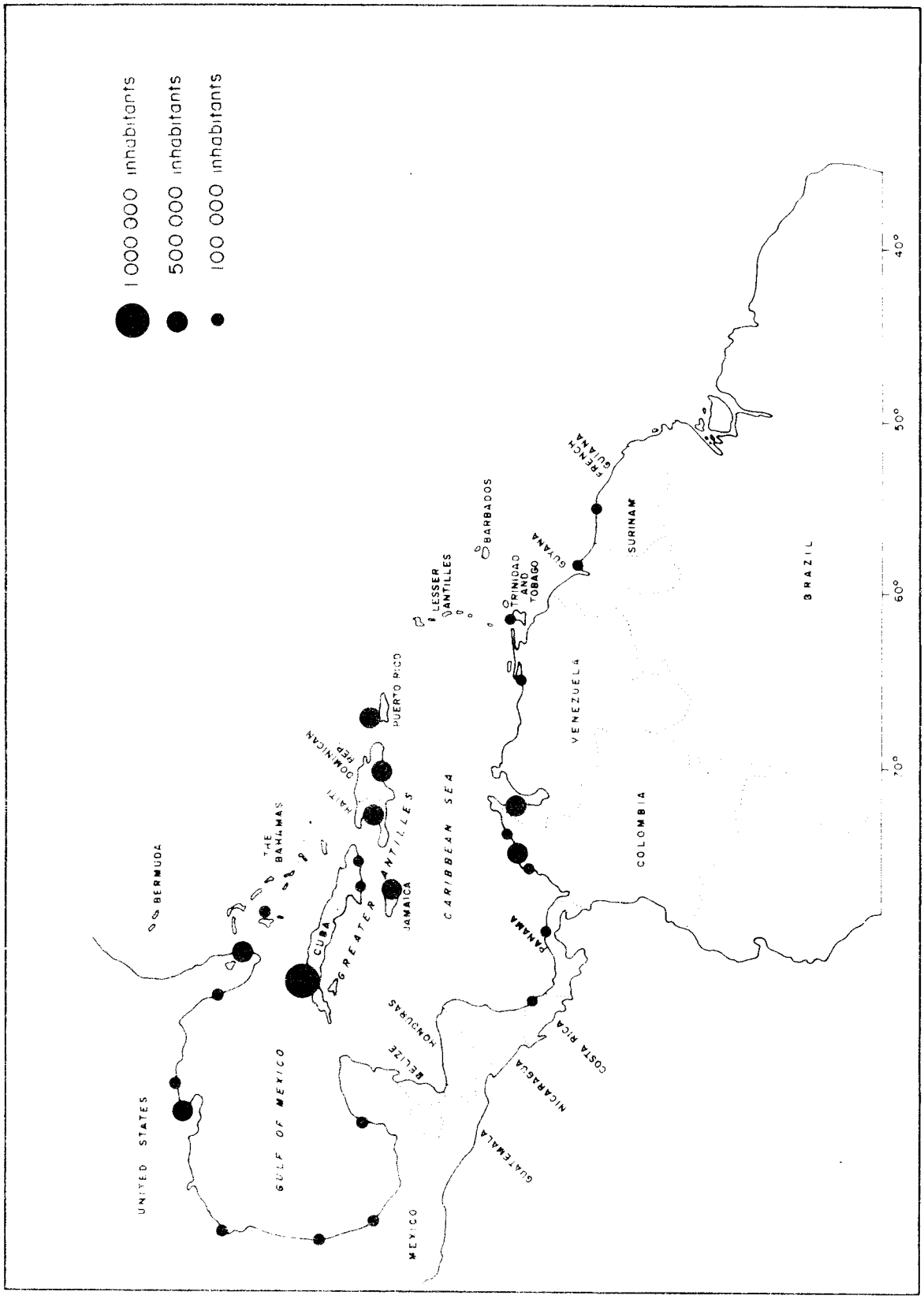

Fig. 5 Population in coastal cities with 100,000 inhabitants or more.

A REVIEW OF RIVER DISCHARGES IN THE CARIBBEAN AND ADJACENT REGIONS

by

J-M. Martin and M. Meybeck

CONTENTS

1. Introduction

The present document describes some major hydrological features and proposes a general methodology for the collection of a first set of water pollution data relevant to rivers flowing into the Caribbean Sea and the Gulf of Mexico.

It is important to bear in mind that the Caribbean Sea is a semi-enclosed body of water (with a volume of about 9.34×10^6 km^3) where any pollution from river discharges will be more detrimental to the marine environment near the river's mouth than in the open ocean.

The total river water discharged to the Caribbean Sea and the Gulf of Mexico is about 1.85×10^3 km^3 per year. The Orinoco river outlet is outside this area, but it is well-known that the main current along the Venezuelan coast is from east to west so that the major part of the Orinoco water flows into the Caribbean Sea. This large-scale east-to-west circulation could also supply some additional water and sediments, but it is at present hardly possible to assess these contributions. Therefore, of these, only the Orinoco river has been included here, in which case the total river discharge comes to about 2.8×10^3 km^3 per year.

It should be noted that if the Orinoco is included the Gulf of Mexico and the Caribbean Sea are fed by two of the world's largest rivers: the Mississippi and the Orinoco.

Despite the importance of these rivers and the potential pollution in this area from surrounding highly-industrial and/or highly-agricultural countries, there has been so far no comprehensive investigation of river pollution, although some work has just started in the development of a World Registry of Rivers Discharging into the Oceans (WORRI) by the International Hydrological Programme and the U.N. Environment Programme. Some intensive work has also been done in the USA mainly by Trefry and Presley on the Mississippi river and by agencies of the federal government through monitoring programmes.

2. General and Hydrological Features of the Region

2.1 Physiography

The total drainage area to the Gulf and Caribbean Sea is about 6.5×10^6 km^2, to which should be added that of the Orinoco basin (0.95×10^6 km^2). The basin covers a wide variety of climates and geomorphological features, from the upper Mississippi basin (50°N) to the Casiquiare river, a tributary of the Orinoco (2°N).

The major mountain ranges are located in the western part of the basin: Rocky Mountains (more than 4,000 m in height), Sierra Madre Oriental (Pico de Arizaba: 5,700 m) and the Colombian Cordilleras (Pico Nevada del Hulla: 5,750 m). The Mississippi and Orinoco basins are the

major low-land areas draining into the Caribbean and adjacent seas; the minor ones are the Yucatan Peninsula, the State of Florida, and Cuba (excluding the Sierra Maestra).

2.2 Hydrology

An estimate of the water input by rivers is given in Table 1. The water discharge from Central America and northern South America is an estimate mainly based on the report of Baumgartner and Reichel (1975) on the World Water Balance. If the Orinoco river is taken into account, the water contribution from the USA would be around 30%, corresponding to about 60% of the total drainage area. Despite their small basins, the Central American rivers from Guatemala to Panama have an important influence on the water budget because of their high specific water discharge (more than 20 $l.sec.^{-1}.km^{-2}$).

The major rivers, according to water discharge (> $200m^3$ $sec.^{-1}$) or to drainage area (> 100,000 km^2), are listed in Table 2. In fact, the Mississippi and the Orinoco are by far the most important rivers, and their contribution alone is more than 55% of the total water discharge. The other important rivers are the Magdalena, San Juan, Coco, Usumacinta, Mobile and the Rio Grande (Rio Bravo).

The river regime is closely related to the climatic features (precipitation and temperature) and may also be influenced by relief in mountainous regions. Several types of rivers can be defined (Guilcher, 1965):

- Northern hemisphere tropical rainy regime: this regime is found in Florida, the Antilles, and from Mexico to Venezuela, which corresponds to about 70% of the waters flowing into the Gulf and Caribbean Sea. The high water period is in September-October and the low water in April-May. There are local variations and two sub-regimes can be defined:

  (i) tropical, with strong single maximum and short low-water period; from Guatemala to western Colombia,

  (ii) tropical single maximum with a longer low-water period; in northern Mexico and Venezuela. The Orinoco belongs to the latter type (high water in July-September, low water in February-April).

- The Mississippi river regime: this regime is very complex owing to the size of the basin (3.25×10^6 km^2) and to the great variety of river regimes, such as the Texan regime, the pluvio-nival and the nivo-pluvial types in the Great Lakes area, the Kansan regime, and the nival and nivo-glacial mountain regimes in the Rocky Mountains. Generally, the high-water period occurs in spring and the low-water period in late summer or autumn, a regime which is close to the pluvio-nival regime found in western Europe.

- Secondary-type river regimes: there are some secondary types of river regimes in the Gulf and Caribbean Sea basin:

(i) The Texan regime is characterized by year-round flow with a maximum in May and a minimum in August-September (in Texas);

(ii) The oceanic pluvial regime has year-round flow with a slight warm-season minimum (e.g., Georgia and Alabama).

The usual high-water period is in April-May and the low-water period in October.

Owing to the great diversity of river regimes, it is obvious that the sampling periods must be adapted to each set of hydrological conditions, especially for the periods of high flow.

2.3 Sediment discharge

As will be seen in section 3, the river sediments play a major role in pollutant transport and availability.

A list of sediment discharge and turbidities of the main rivers is given in Table 3. The Mississippi and the Magdalena (Colombia) rivers are by far the two major contributors of sediments to the Gulf and Caribbean Sea.

Some rivers in Texas and Central America are highly turbid (more than 1g l^{-1}) owing particularly to heavy rains, lack of vegetation cover, and steep slopes. Sometimes the turbidity increases greatly after volcanic eruptions, as was seen after the Irazú eruption in 1964-66 in Costa Rica.

A very rough estimate of the sediment budget of the Gulf and Caribbean Sea is given in Table 4. The average rate of sediment transport is around 130 t km^{-2} per year, which is close to the world average (150 to 200 t km^{-2} per year according to various authors), but there are large variations, with individual values ranging from less than 1 t km^{-2} per year (Apalachicola) to 2,600 t km^{-2} per year (Reventazón, in Costa Rica).

3. River Pollutants to be Monitored

The choice of pollutants to be monitored has been discussed at length in recent years by various international bodies (international conventions and recommendations of international expert meetings). Taking into account these various lists, especially those adopted in some other regional studies, such as the UNEP project on "Pollutants from land-based sources in the Mediterranean", and the various conditions

specific to the Caribbean area, the following list of pollutants is proposed for the first assessment:

i) Extremely hazardous pollutants (black list)

- Arsenic
- Mercury
- Lead
- Cadmium
- Polychlorinated biphenyls (PCBs)
- Other chlorinated organic compounds

ii) Certain other significant pollutants (grey list)

Total organic matter (BOD, COD, or TOC)
Specific organic substances:

- Phenols
- Detergents
- Mineral oils (hexane-soluble)
- Microbiocides

Heavy metals:

- Copper
- Chromium
- Nickel
- Zinc

Nutrients:

- Total phosphorus
- Total Kjeldahl - nitrogen
- Nitrates
- Ammonium

Microbiological pollutants:

- Coliform bacteria

Suspended solids:

- Total suspended matter
- Volatilizable suspended matter

This tentative list calls for several remarks.

i) The importance of a given pollutant varies from river to river; it is thus likely that pollutants other than those listed above might prove to be highly significant and should also be monitored. A typical example is aluminium in Jamaican rivers draining bauxite ores; similarly, iron might be significant in the Orinoco river. Pesticides are other important potential pollutants, especially in Texas and in intensive agricultural regions in the Antilles and Central America. Another specific example is chlorine which is intensively used in fouling control, and released to several U.S. rivers. Chlorine gas, when dissolved in water, readily forms hypochlorous acid and hypochlorite ions ("free available chlorine"). Being a strong oxidizing agent, hypochlorous acid can react with organic compounds to make certain chlorine derivatives (e.g. monochloramine, cyanogen chloride, chlorophenols) known to be toxic to some marine organisms. Chlorine and many of its compounds have been shown experimentally to be toxic to marine organisms at the levels commonly released to the aquatic environment. They can affect primary production and fish life in rivers and estuaries (Hamilton et al., 1970; Carpenter et al., 1972; Gentile et al., 1976), but are usually not monitored or even taken into account in the various lists of pollutants.

ii) Further, the determination of total suspended matter, which can be detrimental to coral growth or to photosynthetic activity, and the analysis of various particulate pollutants including "artificial" particulates, pulp fibres, dairy wastes, asbestos, red-mud, etc., as well as secondary enriched particles and dredge spoils, are highly recommended. In fact, sorption processes may occur in the river watershed (pesticides, heavy metals) and in the river itself, they contribute to the enrichment of the fluvial suspended matter which constitutes a major reservoir of pollution which should be monitored. These particulate pollutants may have detrimental effects on filter feeders, and may lower primary productivity. They can also give rise to soluble pollutants through mobilization processes at the benthic boundary layer. Any balance of pollutants to the Caribbean Sea which did not take into account the particulate phase could lead to an inadequate estimate of pollutant flux and impact.

As an example, the text table below, derived from Trefry and Presley (1976), gives the percentages of some toxic elements supplied to the Gulf of Mexico by the Mississippi river. It shows the major importance of the particulates as carriers of pollutants. Such observations have been made in various other American and European rivers, and this statement is most probably valid for many other pollutants such as PCBs and DDT.

	Zinc	Lead	Copper	Chromium	Nickel	Cadmium	Arsenic
% particulate	90.1	99.2	91.6	98.5	94.7	88.9	70.2
% dissolved	9.9	0.8	8.4	1.5	5.3	11.1	29.8

iii) The differentiation between particulate and dissolved phases is still an open question. The most popular method of separation currently in use is microfiltration. The phase passing through the filter is the so-called soluble fraction while the fraction retained upon the filter is regarded as suspended sediment.

In fact, the separation between various particle sizes is arbitrary, and colloidal or macromolecular material will pass through the filter (usually a 0.45 micron pore size). If we consider the various specific forms of metals in natural waters, described by Stumm and Bilinski (1972), there is obviously a continuous range of metallic species between soluble and particulate phases (e.g. colloidal ferric hydroxide, which is able to pass through a 0.45μ filter, will be retained by a 0.01μ filter). The importance of particulate ferric hydroxides as a scavenger of many heavy metals could then be underestimated by using a 0.45μ pore-size filter. On the other hand, the so-called super-saturation of water with respect to many trace metals is possibly an artefact due to inadequacy in filtration procedure in many cases.

Geochemists are very much aware of this problem but there is still no consensus on its solution. Intercomparison of data from the Caribbean region with those obtained from other regions by the world's hydrological and chemical laboratories will require the use of 0.45μ pore-size filters although there is now evidence that this limit is rather arbitrary and sometimes misleading.

Moreover, it would be very interesting to determine the speciation (crystalline, coating, organic, etc.) of trace elements bound to suspended sediments which could be important for biological assimilation and further remobilization.

4. Rivers to be Monitored

A river quality monitoring network should be based on two considerations:

(i) the greater part of the water discharge should be monitored;

(ii) the greater part of the pollutant input should be monitored.

Therefore we have divided the rivers into four categories which may be overlapping.

4.1 Major rivers

The eighteen major rivers are listed in Table 2; they correspond to 75% of the water input and to 75% of the drainage area. The Mississippi river should be particularly studied because it is by far the largest river, together with the Orinoco, and because it drains a highly-populated (nearly 65×10^6 people), highly-industrialized and agricultural area.

4.2 Rivers assumed to be highly polluted

It is well-known that rivers draining highly industrial or agricultural regions are severely polluted. The Gulf and Caribbean Sea drainage basin is characterized by very important industrial, mining and agricultural activities mainly located in the United States but also in some areas in Mexico, Venezuela, Cuba and Jamaica.

Other important sources of pollution are the urban wastes which are proportional to the size of the city and to its level of development. The total population of the basin can be roughly estimated at 200×10^6 people of which 45% are in the USA, 35% in Central America including the Antilles, and 20% in Colombia and Venezuela. The effects of urban wastes are also dependent upon the distance between the location of the main sewage discharges into the river and the ocean. The most detrimental wastes to the ocean come from nearshore cities. Many big cities are located along the shoreline of the Gulf and the Caribbean Sea: Corpus Christi, Houston, New Orleans, Mobile, Vera Cruz, Baranquilla, La Habana, etc.; they release their wastes through rivers or directly to the ocean.

According to information from some US Federal Government Agencies (Geraghty et al., 1973), a preliminary list of highly polluted rivers in the United States can be given:

Very severe pollution (among the ten most polluted rivers in the USA)	:	Houston Ship Canal (Texas) Escambia River (Florida)
Severe pollution	:	Rio Grande (Texas and Mexico) Brazos (Texas) Mississippi Pearl Mobile (Alabama) Apalachicola (Florida)

Such a list should be set up for all countries according to their potential wastes (mine tailings, agricultural run-off in regions highly fertilized or treated with pesticides, urban wastes, industrial discharges, etc.). The following rivers could be examined: Panuco, Papaualpan and Usumacinta - Grijalva in Mexico, Sinu (copper pollution?) and Magdalena (nitrate pollution) in Colombia, many small rivers in Cuba, Jamaica (bauxite mines), Guatemala (nickel mines), the Orinoco (iron mines), the lake Maracaibo outlet (oil fields) and so on.

4.3 Rivers flowing into sensitive areas

There are many environments along the Gulf and Caribbean Sea coasts where the biotic equilibrium is very sensitive: for example, mangrove areas, lagoons and estuaries, coral reefs and highly productive upwelling zones. These regions are generally characterized by sediment trapping and lower renewal rates of waters, or by highly sensitive organisms, adults (coral reefs) or larvae (estuarine nursery grounds). It is therefore essential to monitor the rivers entering such regions.

4.4 Rivers providing natural background levels

The natural background levels of contaminants in waters are always needed for comparison with the polluted rivers. In some places the natural concentrations in waters or sediments may be very high and exceed the levels required for industrial or drinking water uses. Such natural values will be obtained by monitoring rivers' draining areas with very weak human activities, either industrial, agricultural or mining, and with low settlement densities.

Another interesting point in such studies would be the detection of river contamination by atmospheric fallout, a global phenomenon. This is especially true for pesticides and heavy metals that are carried as aerosols and dust particles (Duce et al., 1974).

Each country should select at least one representative river according to local and regional features.

5. Sampling

5.1 Location of river stations

River stations will be selected as close as possible to the mouth of the river so as to take into account as large a part of the drainage basin as possible.

It is highly recommended to use IHD stations for sample collection. However, the few IHD stations designated at present in the Caribbean region are not always suitable for pollutant assessment and will generally not allow the present flux of pollutants entering the Caribbean Sea because river stations are sometimes located far from the estuarine or deltaic zones. Moreover, pollutants are subjected in estuaries to new physico-chemical, dynamical, sedimentological and biological conditions which may alter their speciation and concentration and their budget to the ocean (Martin et al., 1976). Such important processes will not be considered with the existing IHD river stations. A complementary estuarine and deltaic monitoring programme should be highly recommended.

5.2 Sampling procedure

Usually, water samples are collected at various depths, from just beneath the surface of the river to as close to the bottom as the sampling device will allow. Composite samples will be prepared either from samples collected at various depths and/or by multiple sampling along a cross-section. For small rivers, a depth-integrated sample or a point sample taken at a single transverse position located at the centre of flow is usually adequate.

5.3 Sampling frequency

The determination of sampling frequency is largely dependent upon the required accuracy, the importance of rivers, the hydrological cycle (particularly for non-point sources), the local conditions (existence of sensitive area), and, for point sources, on the pollutant discharge frequency itself. In fact, this latest problem and the existence of accidental pollutant discharge would require a high frequency of sampling which is usually unrealistic from a financial point of view. Prior to the pollutant concentration determination, it is necessary to estimate with accuracy the water and sediment discharge at a gauging station as near as possible to the sampling station.

Taking into account these various considerations it is thought that a first assessment of the pollutant discharge would be made with the sampling time-scales described below:

(i) For the Mississippi river and highly polluted rivers (Escambio, Pearl ... etc.) sampling could be made weekly.

(ii) For major rivers (discharge greater than 200 m^3 sec^{-1}) and "unpolluted" rivers sampling could be performed monthly, except during the high-water period for which two samples per month should be taken.

(iii) Rivers flowing into sensitive areas, a monthly routine sample, with a double frequency during the reproductive periods of sensitive organisms would be adequate.

A further distinction could probably be made with respect to black and grey lists of pollutants, the parameters of the latter being monitored with a lower frequency.

6. Conclusions

Despite the relative scarcity of water quality data, some preliminary conclusions can be drawn.

The Gulf and Caribbean Sea drainage basin is characterized by intensive industrial, mining, and agricultural activities including some major land oil fields, therefore pollution through rivers can be expected to be important in some areas.

In order to assess the pollutants flux from rivers to the Caribbean and adjacent regions the following procedure could be followed:

(i) River monitoring

Different sampling procedures are proposed for four types of rivers:

(a) The Mississippi river should be thoroughly monitored as it could represent alone about 75% of the pollutant load from the USA. It must be remembered that this country represents the major part of the watershed (around 60% of the drainage area, 30% of the water discharge and 45% of the surrounding population*);

(b) The survey of 17 other important rivers (water discharge more than 200 m^3 sec^{-1}) will allow the monitoring of 75% of the waters discharging into the Gulf and Caribbean seas;

(c) In each country small rivers potentially polluted should be listed according to potential pollution from industry, mines, intensive agriculture, or urban waste waters, and be monitored;

(d) Additional rivers flowing to sensitive areas (laguna, fisheries zone) should also be checked and monitored.

(ii) Pollutants to be monitored

Special attention will be paid to extremely hazardous pollutants which are already known to occur in some of these rivers (heavy metals, PCB, pesticides ...). Analysis should be performed both on the water and on the suspended matter.

(iii) Further action

As pollutants can be trapped or their chemical and physical speciation be modified in the estuarine zones, a further monitoring programme on estuaries would give a much more precise flux of pollutants to the Caribbean sea and adjacent regions and also assess the pollution level in these sensitive areas.

As natural background levels of concentrations in waters and in suspended matter are needed for comparison with the polluted rivers, the monitoring of selected rivers should be realized in various non-polluted environments according to each type of water regime and to different geological compositions of the Gulf and Caribbean seas watershed.

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* Orinoco included; if not, these figures are respectively 70%, 42.5% and 45%.

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Table 1

Approximate Water Input by Rivers to the Gulf of Mexico and Caribbean Sea

A. ORINOCO INCLUDED	Total drainage area		Water discharge		
	km^2	%	$m^3\ sec^{-1}$	km^3 per year	%
USA (1)					
Mississippi	3,268,000		18,400	580	
Eastern Gulf	337,000		5,000	158	
Western Gulf	900,000		1,700	54	
Total	4,505,000	61	25,100	792	28
MEXICO (2)	900,000	12	7,300	230	8
GUATEMALA TO PANAMA (3)	365,000	5	14,150	446	16
COLOMBIA (4)	300,000	4	8,500	268	9.5
VENEZUELA					
Caribbean rivers (5)	150,000	2	1,500	47	2
Orinoco (6)	950,000	13	30,000	946	34
GREATER AND LESSER ANTILLES	250,000	3	2,300	73	2.5
Total basin	7,420,000	100%	88,850	2,802	100%

Notes:

(1) Curtis, Culbertson and Chase (1973).
(2) Area estimated; water discharge from Van der Leeden (1975).
(3) Van der Leeden (1975).
(4) Estimated, based on Magdalena figure.
(5) Estimated.
(6) UNESCO (1969).

B. ORINOCO EXCLUDED					
Total basin	6,465,000	100%	58,850	1,856	100%
USA	4,505,000	70	25,100	792	42.5

Table 2

Provisional List of Major Rivers (1)

Criteria of choice : water discharge more than 200 m^3 sec^{-1}
or drainage area more than 100,000 km^2

River	Area (km^2)	Water discharge ($m^3 sec^{-1}$)
USA		
Apalachiocola (Flo.)	44,000	620
Mobile (Ala.)	97,000	1,500
Mississippi (Lo.)	3,268,000	18,400
Brazos (Tex.)	114,000	160
Colorado (Tex.)	107,000	79
USA - MEXICO		
Rio Grande (Tex.)	467,000	23
MEXICO		
Panuco	66,300	549
Grijalva	36,300	723
Usumacinta	47,700	1,763
GUATEMALA - HONDURAS		
Matagua (2)	16,600	252
HONDURAS		
Ulua	22,500	526
Patuca	25,600	825
HONDURAS - NICARAGUA		
Coco (2)	26,700	950
NICARAGUA		
Rio Grande de Matagalpa	19,700	762
NICARAGUA - COSTA RICA		
San Juan (2)	38,900	1,620
PANAMA		
Changuinola	2,745	204
COLOMBIA		
Magdalena	235,000	7,500
VENEZUELA		
Orinoco	950,000	30,000

Notes: (1) Data from Unesco (1969), Van der Leeden (1975), and Curtis, Culbertson and Chase (1973).
(2) International river, figures apply to the whole basin.

Table 3

Sediment Discharge by Rivers into the Gulf of Mexico and the Caribbean Sea (incomplete data)

River	Drainage area at the station (10^3 km^2)	Sediment discharge (10^6t.per year)	Specific transport (t.km^{-2} per year)	Mean turbidity (mg.l.$^{-1}$)
A. Major rivers				
USA (1)				
Mississippi	2,923	222	76	380
Apalachicola	44	0.16	6.8	15
Mobile	95	4.5	42	95
Brazos (Tex.)	114	15.9	139	3,200
Colorado (Tex.)	106	1.9(dam)	17.9	
Rio Grande	467	very low(dam)		
COLOMBIA (2)				
Magdalena	235	235	1,000	1,000
VENEZUELA (3)				
Orinoco	950	85.0	91	90
B. Minor rivers (4)				
EL SALVADOR				
Rio Grande at Moscoco	2,350	0.5	214	
HONDURAS				
Choluteca	1,510		246	
COSTA RICA				
Reventazón	1,367	3.5	2,600 (5)	
Grande	638		126	
NICARAGUA				
Viejo	854		35.8	
PANAMA				
Barjano	3,218		811	

Notes: (1) Curtis, Culbertson and Chase (1973).
(2)(3) Meybeck (1976).
(4) O.M.M. (1972).
(5) Value influenced by the eruption of Irazú volcano.

Table 4

Approximate Sediment Delivery by Rivers to the Caribbean Sea and Gulf of Mexico

Country	Total sediment delivery 10^6 t per year	Reference
USA	343	Curtis, Culbertson, Chase
Central America and Antilles	300	see footnote (1)
Magdalena	235	ref. in Meybeck
Remaining Colombia and Venezuela	50	estimated as (1)
Orinoco	85	ref. in Meybeck
Total	1,013	
Total without Orinoco	928	

Note :

(1) This value has been obtained by multiplying a total drainage area of 1.5×10^6 km^2 by an estimated specific detrital erosion of 200 t.km^{-2} per year.

REGIONAL OCEANOGRAPHY AS IT RELATES TO PRESENT AND FUTURE POLLUTION PROBLEMS AND LIVING RESOURCES - CARIBBEAN

by D.K. Atwood

CONTENTS

1. Introduction

Proper planning for pollution control and abatement cannot completely be done within the framework of isolated national programmes. We must somehow develop international programmes on a regional and even global scale if we are to protect our living resources. Planning for such programmes in marine pollution requires a basic understanding of the oceanography of the region under consideration. This paper is a description of the basic physical and chemical oceanography of one such area - the Caribbean Sea.

2. Regional Description

Figure 1 shows the Caribbean-Gulf of Mexico area in relation to surrounding land and water masses. We can see that the area is relatively land-locked and that its oceanography will be affected by the adjacent North Atlantic waters. Figure 1 also shows two major rivers which empty directly into the area: the Magdalena in Colombia and the Mississippi in the United States. We shall see shortly that at least two other rivers which do not empty directly into the area, the Orinoco and Amazon, also affect it. We shall also see that pollution occurring far from the Caribbean can have definite effects on it, and that occurrences in the Caribbean will affect not only that immediate area, but areas far to the north and east (sections 4.1 and 6.2) as well.

2.1 Regional bathymetry

The land-locked nature of the Caribbean-Gulf of Mexico area is more apparent in Figure 2, where the general bathymetry is shown. We can see that the area consists of a series of deep basins varying from 4.1 to 7.1 kilometres deep and is surrounded on the north, south and west by North, South and Central America; it is partially cut off from the North Atlantic Ocean on the east and northeast by the Greater and Lesser Antilles. Water exchange with the North Atlantic Ocean occurs over the sills between these Antillean Islands. The positions of the major sills are shown in Figure 2. We can see that even the deepest of them, the Windward sill (1,600 metres) and Jungfern sill (1,815 metres) are much more shallow than even the most shallow basin. For this reason, much of the water in the Caribbean is below sill depth, causing much concern about the extent of renewal of these waters. We shall discuss some implications of this later (sections 3.2 and 6.3).

3. Water Masses of the Caribbean Sea

3.1 General features

Water masses or types are usually defined in terms of their origin. The origin of deep waters is in turn defined by the point at which the water was last at the surface of the sea where exchanges across the air-sea interface and biological activity gave it a particular salinity, temperature and oxygen concentration. After leaving the surface, the water mass can be altered only by mixing, respiratory processes, and other relatively slow chemical reactions between the water and suspended matter. Other than mixing, these processes

will have little effect on salinity and temperature; however, respiration and/or decay of detritus can alter nutrient and oxygen concentrations. During these processes, the water develops specific temperature, salinity, oxygen and nutrient **characteristics**, which, when considered together, can be used to identify - or "fingerprint" - the water mass. The depth at which these characteristics are most pronounced is referred to as the core depth for that water.

Figure 3 shows the approximate core depths for water types present in the Venezuela Basin of the Eastern Caribbean Sea. These same water types can be traced through the other basins and into the Gulf of Mexico. Note that above 500 metres, the core depths are noticeably more shallow in the south than in the north of the basin. This is an important fact which will have bearing on later discussions (section 4.3.1). Table 1 gives a summary of the origin and characteristics of each of these cores. Mixing occurs between water cores, and the parameters that define the adjacent cores show almost linear mixing curves. This is aptly illustrated in Figures 4 and 5, which show profiles of salinity and dissolved oxygen versus depth for the Northern Venezuela Basin. In Figure 4, we can see that the salinity curve is essentially linear between the surface mixed layer and the salinity maximum at about 175 metres (Subtropical Underwater), and again between the salinity maximum and the salinity minimum at about 800 metres (Subantarctic Intermediate Water). The oxygen profile in Figure 5 shows a slight oxygen maximum at about 300 metres for the 18°C Sargasso Sea Water (Kinard et al., 1974), a mimumum at about 700 metres for the Subantarctic Intermediate Water and another slight maximum between 1,600 and 1,800 metres. This slight maximum has been attributed by Wüst (1964) to overflow of North Atlantic Deep Water over the Jungfern sill into the deep Venezuela Basin. Again the mixing portions of the curve between cores is almost linear. The oxygen minimum at about 700 metres is due to respiration and decay of organic detritus depleting dissolved oxygen. Note that at deep depths the oxygen concentration is quite high, reflecting the cold temperature of the source of these deep waters and resulting in an enhanced oxygen solubility where the water was formed at the surface. The slight oxygen maximum at 300 metres is similarly a reflection of the enhanced oxygen solubility at that water's source in the relatively cold (18°C) Sargasso Sea during winter.

3.2 Renewal of deep water

As mentioned above (section 2.1), since much of the water in the deep basins of the Caribbean is below sill depth, there is concern over the extent to which this water is renewed. In section 3.1, we pointed out that a slight oxygen maximum in the Northern Venezuela Basin at approximately the same depth as the Jungfern sill has been interpreted by Wüst (1964) as "renewal water" flowing over that sill. We also pointed out that deep Venezuela Bottom Water is rich in oxygen and appears well ventilated in contrast to anoxic conditions which would prevail if no renewal had occurred. Therefore, either some renewal is occurring or has occurred in relatively recent time.

How much is occurring or how long ago it occurred is a question presently of concern to many researchers. Worthington (1955 a, b) has considered oxygen and temperature data taken in the Venezuela Basin from 1933

to 1954, and concluded that during that period oxygen values had dropped and the temperature increased at a rate that indicated renewal of Caribbean Bottom Water had not occurred for between 150 and 500 years. Serious doubt, however, developed as to whether oxygen data for the period were precise enough to warrant such comparison. Wüst (1964) presented potential temperature sections through the deep Caribbean passages that indicate continuity between the North Atlantic Deep Water and Caribbean Bottom Water. However, using 1963 CRAWFORD hydrographic data directly across the Jungfern and Windward sills, Worthington (1968) showed that discontinuities in the potential temperatures occurred at the sills indicating that no deep renewal was occurring at that time. More recently, work by Metcalf and Stalcup (1973), Stalcup et al. (1975), Sturges (1975), Froelich and Atwood (1974), and Atwood et al. (1976) had demonstrated that at least small amounts of cold North Atlantic Deep Water are flowing over the Jungfern sill into the deep Venezuela Basin.

Froelich and Atwood's (1974) conclusion is based on a temporal study of deep silicate data at a serial station just southwest of the Jungfern sill. Figure 6 shows profiles of dissolved silica versus depth for the North Atlantic just north of the Jungfern sill and for the Caribbean just southwest of it. The Caribbean station shows a low concentration (1-4 µm) of dissolved silica at the surface due to depletion by marine organisms, and high values (28 µm) in deep water where the silica is returned by the sinking and decay of these same organisms.

However, the curve for the North Atlantic shows a distinct difference in dissolved silica concentration at the depth of the sill (15 to 16 µm), as compared to the Caribbean water of the same depth (28 µm). Therefore, if North Atlantic Deep Water crosses over the sill, we should be able to see a dilution of dissolved silica in the Caribbean Bottom Water at least near the sill. Salinities on both sides of the sill are very close, and cannot be used to this same purpose.

Figure 7 shows the results of Froelich and Atwood's (1974) two-year temporal study of deep dissolved silicate just inside the sill. At about the sill depth and below, there is definite evidence that dilution of dissolved silica occurs, and it seems to occur sporadically. Thus, at least some renewal occurs. Worthington (personal communication) contends that the amount of renewal demonstrated is miniscule and not sufficient to have any major effect on deep Caribbean Water. However, Atwood et al. (1976) showed that this renewal can be demonstrated to have an effect on deep silicates of the northern Venezuela Basin, the mean deep silicate concentration of the northern part of the basin being some 1.5 µm less than that for the southern part. We will consider this again later (section 6.3) when we discuss possible effects of pollutants.

3.3 Surface water

We have not discussed the surface mixed layer of the Caribbean, nor does Table 1 list its origin or characteristics. This layer, and in fact the upper two hundred metres of the Caribbean, is greatly affected by circulation. We must, therefore, first consider the currents in the area before we can consider the surface water.

4. Circulation in the Caribbean Sea and Gulf of Mexico

4.1 Ocean currents

To properly understand the current structure of the Caribbean-Gulf of Mexico area, we must first consider the rest of the ocean. The basic forces exerted on the sea surface include the wind and Coriolis force. The wind exerts a frictional force on the surface of the sea which is transmitted downward because of the viscosity of the water. This tends to move the water in the direction of the wind, however, due to rotation of the earth, a second virtual force - the Coriolis - is applied at right angles to any moving body on the earth's surface. In the northern hemisphere, this deflects the body to the right. This force is zero at the equator and increases towards the poles. Usually this force is not perceptible since other forces are much larger. However, in the case of the ocean and air currents, the Coriolis force is of the same magnitude as other forces and has a definite effect on circulation.

Figure 8 presents the world's ocean current system; Table 2 gives the names of major currents, keyed to the numbers in Figure 8. Note that in each northern ocean, a clockwise gyre system exists with diffuse eastern currents and very strong currents near the western land boundaries. These latter currents are called Western Boundary Currents and include the Kuroshio and the Gulf Stream. In the southern oceans, the gyre system is counter-clockwise. The Antarctic Circumpolar Current in the extreme southern oceans is the area where the most important ocean mixing occurs, since it extends through the southern end of all three major oceans: Atlantic, Pacific and Indian.

It is clear from Figure 8 that the Caribbean-Gulf of Mexico area has inputs from the Equatorial Currents of both the North and South Atlantic and that output from the system will be soon dispersed through the entire North Atlantic gyre system.

4.2 Currents in and adjacent to the Caribbean Sea and Gulf of Mexico

Figure 9 shows the current system of the Caribbean and Gulf of Mexico as well as its inputs and outputs. Currents providing inputs are the North Equatorial Current and Guiana Current, which is an extension of the South Equatorial Current. These enter the Caribbean through the lower passages of the Lesser Antilles and become the Caribbean Current, which passes through the Caribbean, the Yucatan Straits, the southeastern Gulf of Mexico and the Straits of Florida. During this passage, various smaller currents or eddies develop which vary seasonally, such as the countercurrents in the northern Caribbean, the loop in the Gulf of Panama, and the Gulf Loop Current.

The Caribbean Current has a maximum transport of the order of 26-34 million m^3 of water per second (Gordon, 1967). Stalcup and Metcalf (1972) have shown that enough water passes through the lower passages of the Lesser Antilles to account for all of this. The same magnitude of transport occurs through the Yucatan Straits and the Straits of Florida, after which

the Caribbean Current is joined by the Antilles Current (or Canary Current) and transport reaches a value of the order of 55 million m^3 of water per second (Neumann, 1968).

4.3 Measurement of ocean currents

There are essentially three methods of measuring the magnitude and direction of ocean currents. Two are direct methods: Lagrangian measurements using drifters or drogues; and Eulerian measurements using current meters. Drifters or drogues are marked and released, and must either be tracked by ships, airplanes or satellites, or the investigator relies on recovery and return of the drifters by someone else and tries to deduce the path followed. Current meters must be moored and held relatively stationary either by securely anchored ships or by deep anchors with acoustical releases which can be triggered from a surface ship when the investigator desires. Due to the time and expense involved with drogue tracking and deep mooring of current meters, investigators often use a third indirect method of measuring ocean currents called the dynamic method.

4.3.1 The dynamic method of measuring ocean currents as applied to the Caribbean

The Caribbean Current itself can provide us with an excellent example for demonstrating the dynamic method of measuring ocean currents. At the same time, we can learn more important facts about the circulation in the Caribbean. In section 4.1, we discussed the Coriolis force which acts perpendicular to the direction of motion in such a way as to turn it to the right in the northern hemisphere. Thus, in the Caribbean, the Coriolis force is directed northward against the westward flowing Caribbean Current. This results in movement of Caribbean surface water northward until it piles up against the barrier of the Greater Antilles. This results in a slightly higher sea surface level at the north end of the Caribbean, and a "distortion" of the density field so that a pressure gradient is directed southward that just balances the Coriolis force. The result is a "distortion" in the density field that is proportional in magnitude to the current flowing west. Thus, if we can measure accurately the differences in the pressure field and relate them to a zero motion reference level, we can calculate the velocity of the current: this is basically the dynamic method. The measurement is accomplished by sampling a section of hydrographic stations along a line at right angles to the current direction, and carefully determining the salinity and temperature as a function of depth.

Figures 10 and 11 show a salinity and temperature profile across the Caribbean at 67°00'W. We note that the contours for both salinity and temperature generally slope upward towards the south just as the core depth does for the Subtropical Underwater and 18°C Sargasso Sea Water (section 3.1). The result is a greater thickness of warmer, fresher water at the north end of the section where it has been pushed by the Coriolos force creating a pressure gradient to balance it. Thus on the south end along the Venezuela coast, colder, nutrient-rich water is closer to the surface where upwelling along the coast can bring nutrients into the photic zone resulting in greater productivity. We also note that both the salinity and temperature contours turn slightly upward at the extreme north end of the section.

Figure 12 shows the current velocities calculated from the data in Figures 10 and 11. Shaded areas depict eastward flow (into the page) and unshaded, westward flow (out of the page). In Figure 12 we should note the following:

(i) The major flow of the Caribbean Current in June 1972 occurred in two branches; one between 16°00'N and 14°00'N and the other between 13°30'N and 12°00'N. Surface current velocities in these branches were very high; > 40 cm sec^{-1} and > 60 cm sec^{-1} respectively.

(ii) An extensive countercurrent covered the northern third of the section from 18°00'N to 16°00'N and had surface velocities of > 25 cm sec^{-1}. This eastward flowing current is what caused the slight upward tilt in temperature and salinity contour in the north in Figures 10 and 11.

(iii) Significant flow (> 5 cm sec^{-1}) occurs as deep as 500 metres, but not below that depth.

The seasonal nature of the eastward flowing countercurrent shown in Figure 12 is demonstrated in Figure 13, which shows velocities for the same section four months later in October, 1972. At that time, the two branches of the Caribbean Current were in approximately the same position with the same surface velocities as in June 1972, although significant velocities occurred deeper (1,000 metres). However, the counter-current consisted of only a narrow band just north of the northern branch of the Caribbean Current, and most of the northern third of the section exhibited relatively weak westward flow.

Through June 1975, data for nine such sections have been collected and reduced. Although data interpretation is not complete, it can be said that:

(i) The maximum current velocities are always in the southern half of the Caribbean.

(ii) An eastward flowing current always exists somewhere north of 14°30'N.

(iii) The net westward transport above 1,600 metres varies from about 15 to 28 million m^3 sec^{-1}.

In late 1975 and early 1976 a series of satellite-tracked Langrangian drogues were released in the eastern Caribbean and, as they were tracked, density sections such as the above were also taken. A comparison of the drogue tracks and geostrophically calculated currents indicates that the indirect measurements are essentially correct, but that the flow regime is quite variable in space and time.

5. Origin of Surface Water in the Caribbean Sea and Gulf of Mexico

5.1 Salinity variations

There is a distinct variation in surface salinity in the Caribbean with relatively high (> 35.5°/oo) salinities between January and May, with

highest salinities (> 36.5°/oo) occurring in February and March, and lower salinities between June and December, with a minimum (> 34.5°/oo) occurring in October and November. This is illustrated in Figures 14 and 15, which are adapted from Wüst (1964). The figures give a clear indication that the low salinity water that occurs in late fall enters the Caribbean from the south and east, which is the "source area" for the Caribbean Current. There has been some conjecture as to the source of this water, with some people arguing that its source is the tropical convergences close to the equator where there is extensive rainfall, and others that its source is the Amazon and Orinoco rivers which have maximum discharge between February and April (Wüst, 1964).

Tremendous amounts of water flow out from the Amazon river. Davis (1964) and Oltman (1968) report an average annual outflow equal to about 30% of all river water reaching the entire Atlantic. Wüst (1964) has summarized data through 1964 that show that the mean discharge of the Amazon is 106 to 124 m^3 sec^{-1} and a maximum discharge of 146 m^3 sec^{-1}. The Orinoco discharge is less, but still has a mean of 14 to 34 m^3 sec^{-1} and a maximum of 65 m^3 sec^{-1}. Thus, these two rivers can add between 125 and 200 m^3 sec^{-1} of fresh river water to the oceans. The surface currents depicted in Figure 9 are ideal for transporting this water into the Caribbean.

5.2 Silicate-salinity relationships

If the low-salinity surface water found in the Caribbean in October and November has its source in the Amazon and Orinoco rivers, the silicate concentration of the Caribbean surface water should show it. Due to weathering of rocks and soil, river waters carry high concentrations of dissolved silica. The Amazon and Orinoco contain 9-14 ppm dissolved silica (Livingston , 1963), whereas rain water should contain almost no dissolved silica unless it is from dust particles. Thus, if river water is the source of low-salinity Caribbean Surface Water, there should be an increase in silica as the salinity decreases. Froelich, Atwood and Polifka (1974) have reported results that show that this is exactly the case. Figure 16 shows their silicate and salinity data collected at the PESCA serial station in the Northern Venezuela Basin. It is clear that during the low-salinity periods there is a concurrent increase in dissolved silicate concentration. The same data are plotted in Figure 17 to show that there is a clear linear relationship between silicate and salinity so that there is little doubt that the low-salinity water is fluvial in origin. The authors showed a similar relationship for stations all across the Venezuela Basin, proving that the source could not be local run-off from nearby islands, and concluding that the low-salinity water originated in the Amazon and Orinoco rivers.

Since the presentation of Froelich, Atwood and Polifka's (1974) results, Carder and Schlemmer (1973) at the University of South Florida have identified nepheloid layers (layers of finely divided sediment suspended in the water column) throughout the Caribbean and Gulf of Mexico, which have sources in the Amazon and Orinoco. These layers are not restricted to the surface water, and occur at depths where particle and water densities are such that the particles remain suspended. One such layer occurs in the high salinity core of the Subtropical Underwater (Figure 3), which is at a depth where significant transport of this material can occur (Figures 12 and 13).

Another fact which should be noted in Figures 14 and 15 is the high salinities that occur along the southern portion of the Caribbean all year round as compared to salinities to the north. As discussed in section 4.3.1, this is a result of the Caribbean Current and balancing Coriolis and pressure gradient forces which have pushed the warm, lower-salinity surface water northward, exposing the upper part of the high-salinity Subtropical Underwater. As a result, cold, nutrient-rich water is closer to the surface near Venezuela and Colombia, and coastal upwelling can bring it into the photic zone, increasing productivity many times.

Another input of fresh water which has an interesting local effect is large seasonal amounts of rainfall which occur in the southwest area of the Caribbean near Panama. This rainfall produces low-salinity surface water which "floats" on the sea surface producing the anticyclonic gyre (rotation opposite to normal Coriolis-produced circulation), or loop current, near the Gulf of Panama (Figure 9).

There are various other important inputs of fresh water from rivers such as the Magdalena, Mississippi and smaller rivers draining Mexico, Central America and the United States. All of these have local importance, and the effects of the Mississippi and Magdalena on sedimentation are felt quite far from their source. However, none of these has an oceanographic impact like the Amazon and Orinoco rivers.

6. Present and Future Pollution Problems Considered in Relation to the Oceanography of the Caribbean Sea

6.1 General considerations

The foregoing sections provide an oceanographic framework in which we can consider the possible impact of present and future marine pollution. Unfortunately, we are somewhat limited in this respect, since not all of the present or potential pollution sources are known to us. Recent attempts by the Intergovernmental Oceanographic Commission to fill this gap in knowledge through the Co-operative Investigations of the Caribbean and Adjacent Regions (CICAR) have so far failed, with less than 15% of member nations responding adequately to a pollution questionnaire which was sent out to prepare for this Workshop. Nevertheless, we do know some sources and can consider what oceanographic impact any sources might have.

Based on the oceanography discussed in the foregoing sections, we can consider pollutants according to their possible effects on two categories of water:

(i) The upper 1,500 metres of the Caribbean-Gulf of Mexico area, with special emphasis on the upper 500 metres where most transport occurs, and

(ii) The deep water below the sills where renewal is a problem.

6.2 Consideration of the upper 1,500 metres of water

In sections 3, 4 and 5 we have considered the water masses present in the Caribbean and Gulf of Mexico and the currents that transport them. We have seen that these waters have origins as far away as 60°S (Subantarctic Intermediate Water) and from places as varied as the Sargasso Sea (18°C Sargasso Sea Water), the mid-latitudes of the North Atlantic (Subtropical Underwater) and the Amazon and Orinoco rivers (low-salinity surface water). Obviously, pollution of any of these sources, or of places between these sources and the Caribbean will affect the area and its living resources. For example, development in the Amazon river or Orinoco river drainage basins could increase the amount of suspended material added to the system and a portion of the pollutants deposited there, such as pesticides, herbicides, or heavy metals, will probably find its way into the Caribbean within a year.

We have also seen that water that flows through the Caribbean becomes part of the Gulf Stream and is distributed throughout the North Atlantic gyre system and eventually the entire world's oceans. Pollutants added to the water during this transit will be distributed in the same way. The time scale for such distribution is probably 1 to 5 years for the North Atlantic surface waters and over one thousand years for the entire world ocean unless the materials are removed by some process before mixing can occur.

A consideration of one type of potential pollution source in the Caribbean can serve as an example of what type of problems can occur. The Caribbean is an area of active petroleum production and refining. It is interesting to consider the current system diagrammed in Figure 9 in the light of some of the more active specific sites of petroleum and petrochemical activity such as Trinidad, St. Croix, Puerto Rico, Aruba, Curaçao, Lake Maracaibo, Jamaica and the Gulf coast of the United States where extremely large petrochemical complexes exist in the Galveston Bay and Mississippi river areas, and extensive amounts of offshore oil, gas and sulphur are produced. Added to these is the constant traffic of large and small petroleum tankers which cross the area. Even if these ships do not have accidents that result in spills of oil, they must constantly flush their tanks with ballast water, which results in significant transfer of hydrocarbons from the ship to the water (Sackett, 1974).

The reefs off the small fishing village of La Parguera, Puerto Rico, have been subjected to at least two groundings of large petroleum tankers in less than two years. One of these resulted in a major spill which extensively damaged shores and marine life. However, even more insidious than the oil spills, which can cover large areas of ocean surface and shoreline, is the organic matter that becomes dissolved in the seawater following oil spills. Brooks and Sackett (1973) surveyed the distribution of dissolved C_1- to C_4-hydrocarbons in the Gulf of Mexico, and showed important man-made sources associated with ports, offshore petroleum drilling and production operations, and open-ocean shipping activity. More recently, Sackett (1974) has presented direct evidence that large amounts of these hydrocarbons are added by underwater gas flares near oil-drilling rigs, and by ballast pumping from petroleum tankers. What the effect of these hydrocarbons on marine life can, and will, be is not completely known, but indications are that they can be deleterious.

There are no similar data on dissolved hydrocarbons in the Caribbean Sea; not even background data. However, in view of the extensive petrochemical activity bordering the Caribbean, chances are very high that hydrocarbons are being dissolved in surface sea-water throughout the area.

6.3 Consideration of the deep water

In section 3.2 we discussed the problem of renewal of deep water in the Caribbean basins, and pointed out that apparently very little renewal or flushing occurs. Thus pollutants that find their way into this water will not be flushed out. Perhaps we could adopt the perverse attitude that if we dump materals into these basins, at least we are localizing the dump; however, if pollutants are added in sufficient amounts, they could create severe problems and eventually even cause anoxic conditions.

The mechanisms by which pollutants can find their way into the deep water during a relatively short time include:

(i) As part of the suspended or nepheloid material that gradually sinks toward the bottom water. Pollutants such as pesticides or heavy metals absorb very easily on the high surface area presented by these fine particles and can be transported down as part of the absorbed phase.

(ii) As part of the sinking and decaying fragments of dead marine organisms which either ingested the material at the surface or absorbed it from the dissolved phase.

Much of this material would eventually be transported to the sediments, but, as organisms decay, a significant portion would be returned to the dissolved phase. The decay of any labile organic material will deplete the amount of dissolved oxygen, which could eventually result in anoxic conditions. Worthington (1955a) postulated that natural processes had depleted the dissolved oxygen in the deep Venezuela Basin by 0.3 ml l^{-1}, or approximately 6%, in about 20 years. Addition of large amounts of material derived from human activities could significantly increase this rate so that whatever renewal occurs could not keep up, and anoxic conditions could prevail.

We do not know just how fragile the deep-water system of the Caribbean-Gulf of Mexico is; however, until we do, great care should be exercised and we should attempt to learn more about the entire system so that we can use it to our maximum advantage while still protecting it.

7. Summary and Conclusions

In this paper we have discussed the basic oceanography of the Caribbean and Gulf of Mexico as it relates to marine pollution. We have seen that Caribbean-Gulf of Mexico pollution could have sources far from that area, and pollution in the area could affect vast areas of the world's oceans and shorelines. At the beginning of the paper, the need for international programmes in pollution monitoring, control and abatement was mentioned, and I hope that that need is more clear to us now. If anyone can have an impact on starting such programmes, it is those, such as the participants in this Workshop, who are closely involved with various governments and their pollution control agencies, which should be urged to consider such programmes for which the reading of the chapter entitled "Design of a World Monitoring System" by A.J. Lee et al. (1972) in "A Guide to Marine Pollution" is highly recommended.

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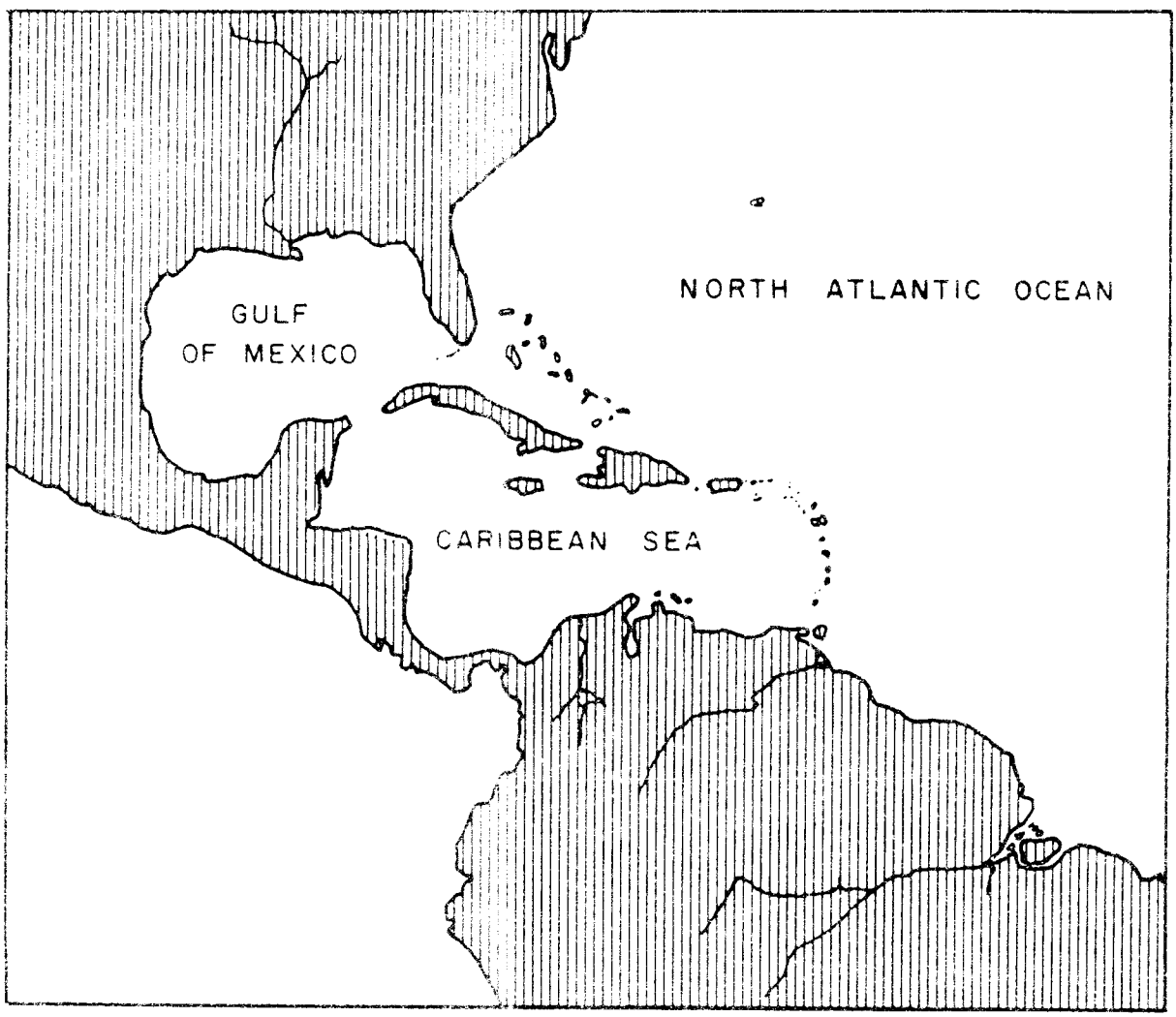
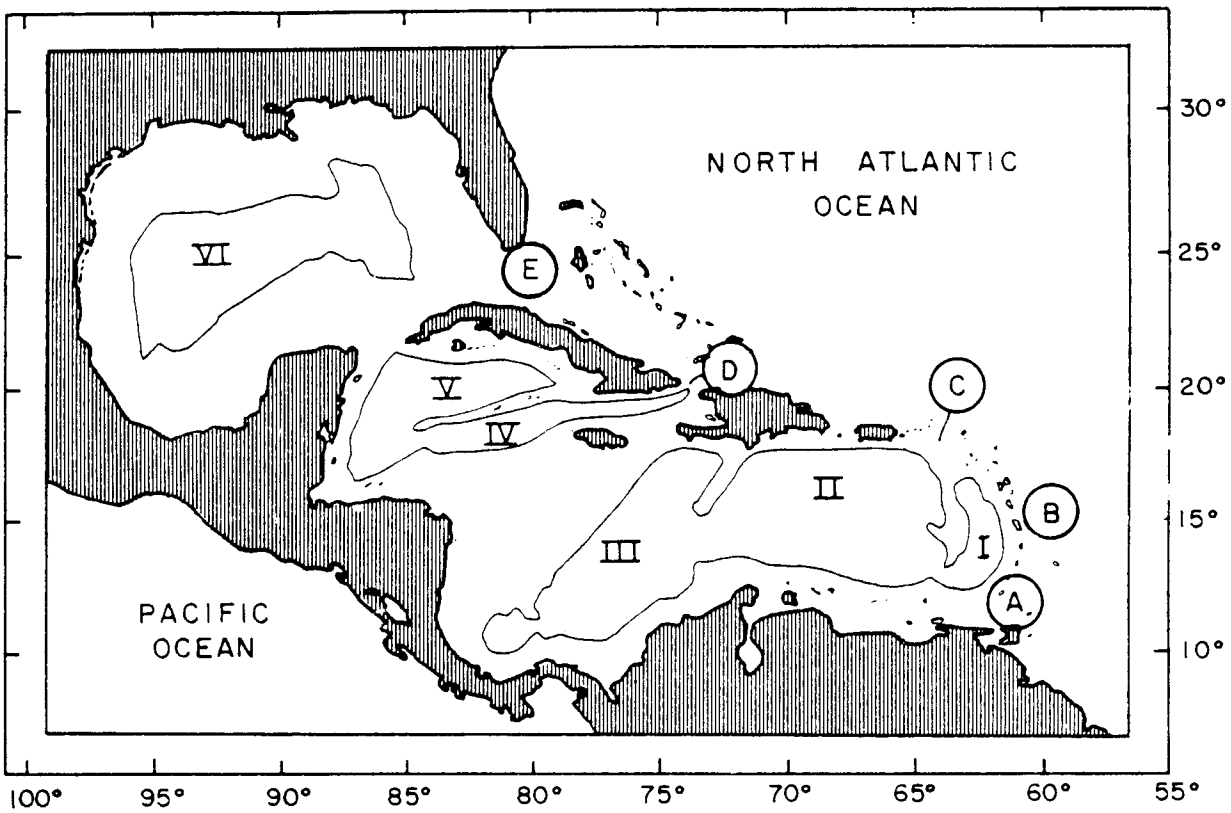


Fig. 1 The Caribbean-Gulf of Mexico region (The American Mediterranean) in relation to surrounding land and water masses and principal rivers.



I	GRENADA TROUGH	4100 m	A	GRENADA and ST. VINCENT SILLS	1000 - 1400 m
II	VENEZUELA BASIN	5600 m	B	ST. LUCIA SILL	800 m
III	COLOMBIA BASIN	4500 m	C	JUNGFERN SILL	1815 m
IV	CAYMAN TROUGH	7100 m	D	WINDWARD SILL	1600 m
V	YUCATAN BASIN	4600 m	E	STRAITS OF FLORIDA	800 m
VI	MEXICO BASIN	4400 m			

Fig. 2 General bathymetry of the American Mediterranean Sea showing major basins (roman numerals) and sills (letters). The names and depths of these features are given below the figure. (Adapted from Svedrup, Johnson and Fleming, 1942.)

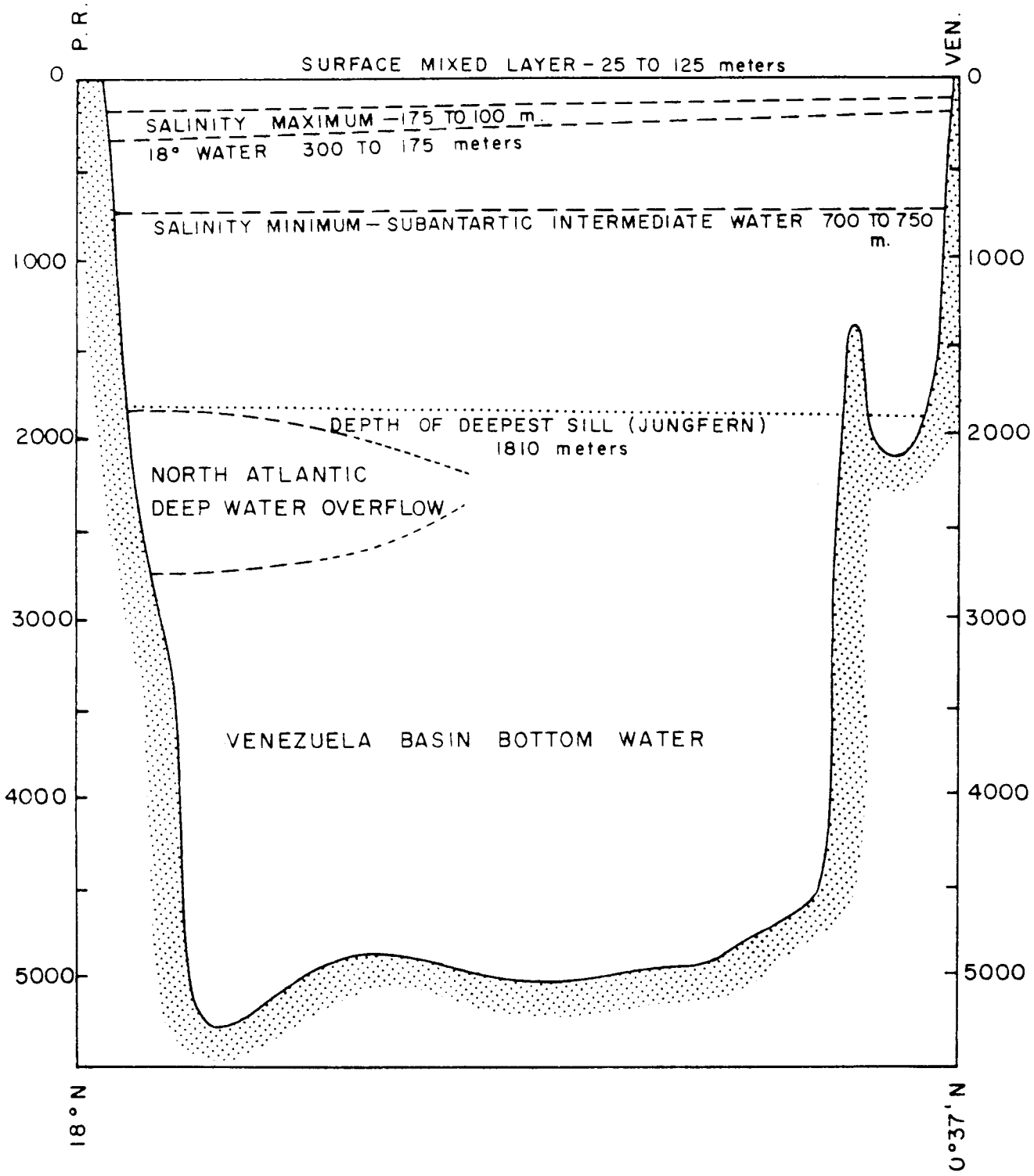


Fig. 3 Approximate core depths for water cores in the Venezuela Basin of the Caribbean Sea (adapted from data in Wüst, 1964).

Table 1

CHARACTERISTICS OF THE WATER MASSES IN THE BASINS OF THE CARIBBEAN SEA

Type of water	Origin	Temperature °C	Salinity °/oo	Oxygen ml l^{-1}	Silicate µm
Subtropical Underwater (100 to 175 m)	At the surface at 20° - 25°N & 55°W	22 to 24°	36.80 to 37.02 (maximum)	4.2 to 4.5	1.0 to 2.0
18°C Sargasso Sea Water (175 to 300 m)	At the surface of the Sargasso Sea in winter	17.9 ± 0.5°	36.50 ± 0.2	Maximum 5.0 inversion	3.0 to 5.0
Subantarctic Intermediate Water (700 to 750 m)	At the surface at 60°S	6.5 to 7.5°	34.74 (minimum)	2.86 to 3.10 (minimum)	23.0 to 27.0
North Atlantic Deep Water Overflow (1800 to 2500 m)	Flow over the Jungfern Sill into the Venezuela Basin	4.1°	34.98	4.9 to 5.1	23.0 to 25.0(1)
Bottom Water	Rate of renewal unknown	4.1°	34.98	4.9 to 5.1	27.0 to 30.0(1)

Notes : (1) In the Cayman Trough the water below 4.1°C in temperature contains as much silicate (15 µm) as is found in deep Atlantic water.

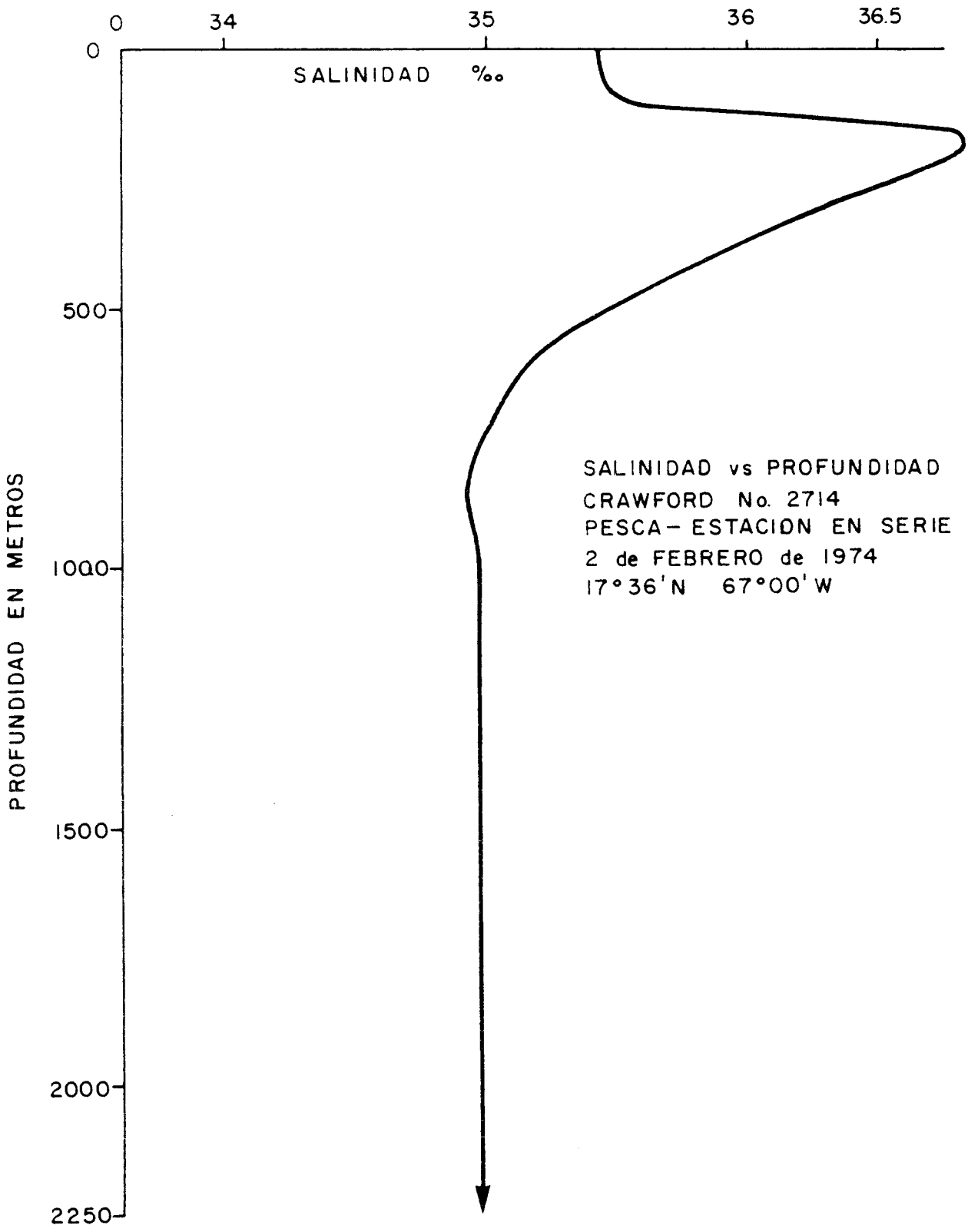


Fig. 4 Profile of salinity versus depth for R/V CRAWFORD Station Number 2714, 2 February 1974, at 17°36'N and 67°00'W (North end of Venezuela Basin). (Programa Estudios Caribe, Universidad de Puerto Rico.)

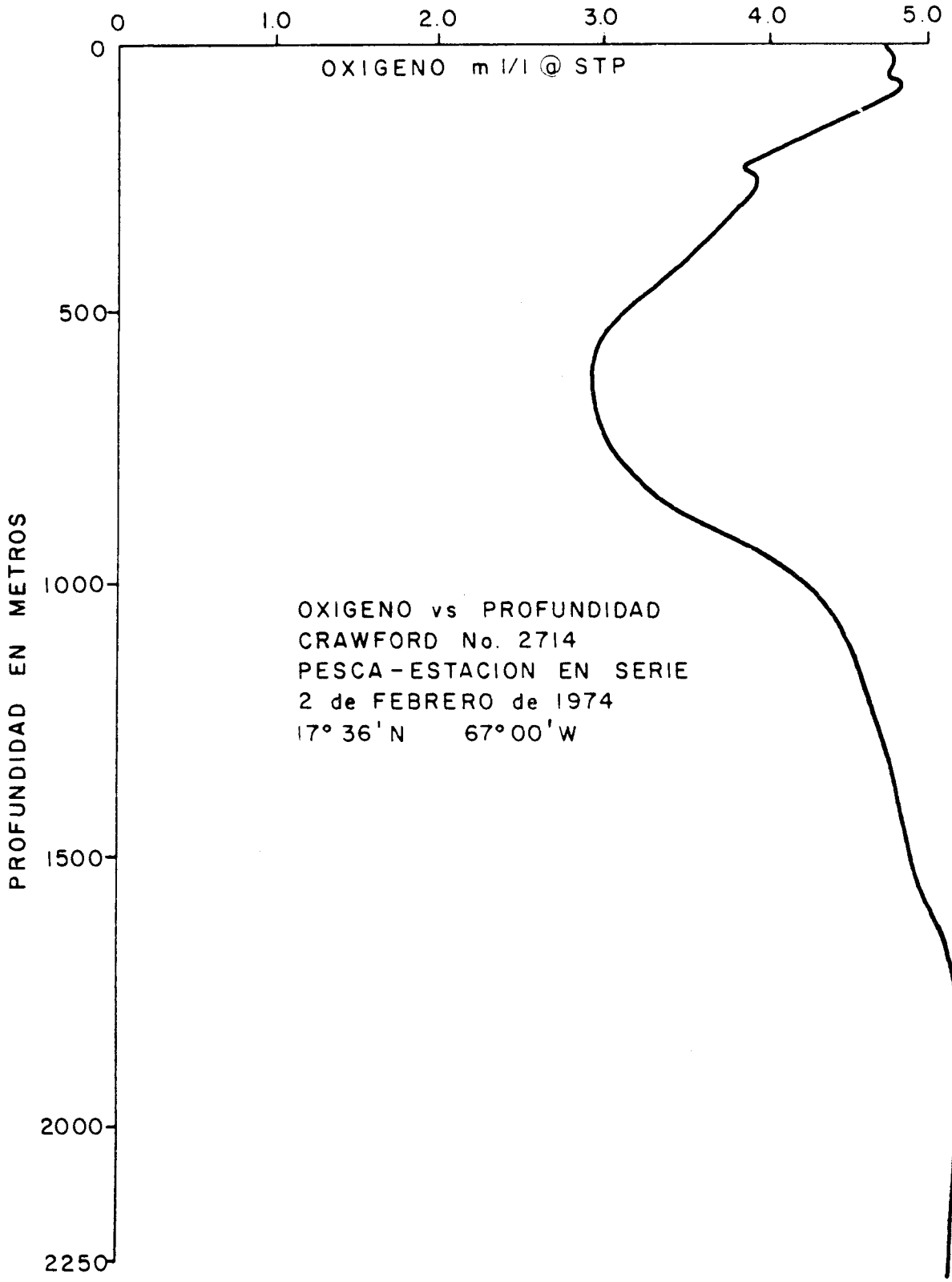


Fig. 5 Profile of dissolved oxygen versus depth for R/V CRAWFORD Station Number 2714, 2 February 1974, at 17°36'N and 67°00'W (North end of Venezuela Basin). (Programa Estudios Caribe, Universidad de Puerto Rico.)

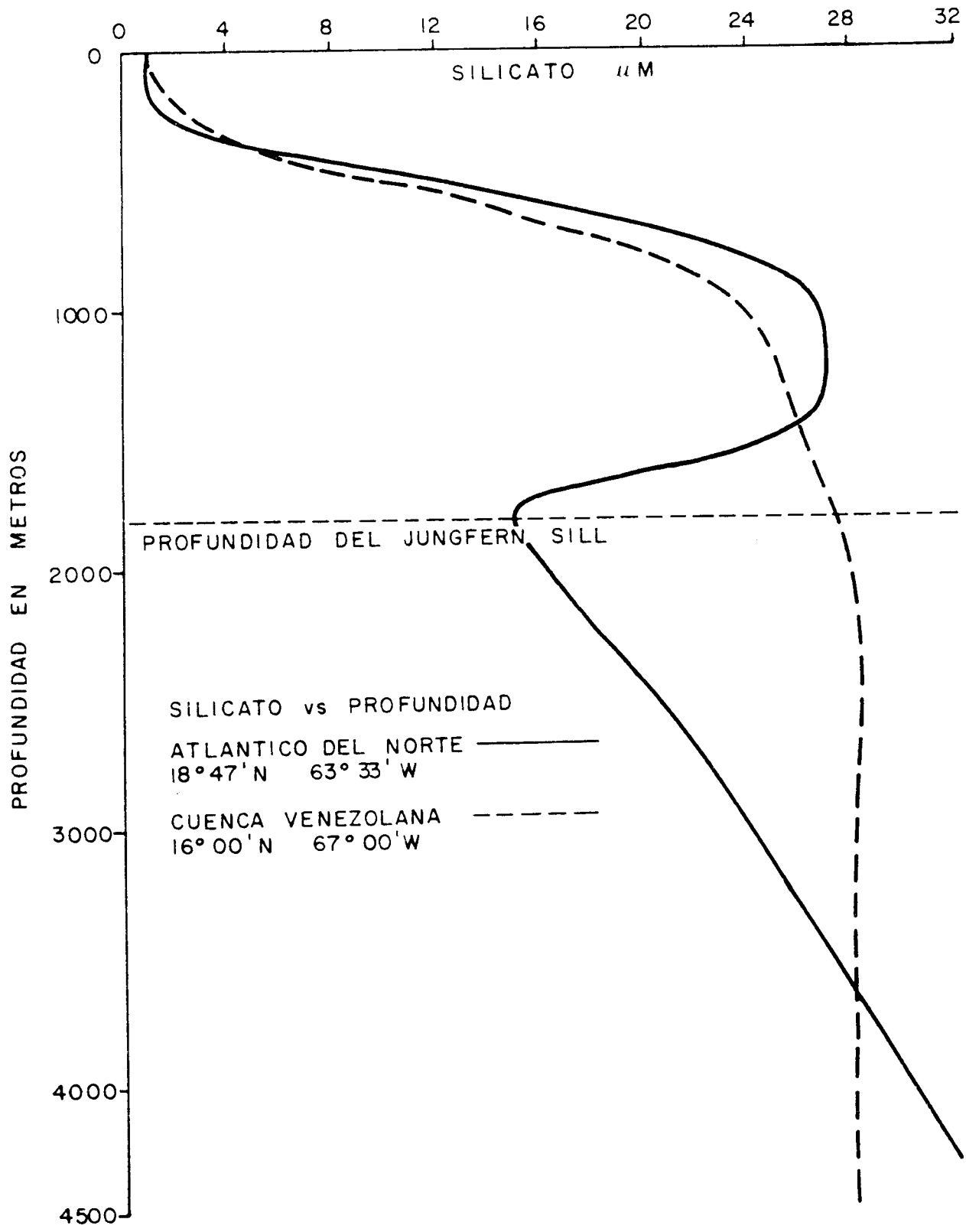


Fig. 6 Profile of dissolved silica versus depth for stations just north (18°47'N, 63°33'W, KNORR Station 198) and just southwest (17°36'N, 67°00'W, CRAWFORD Station 2714) of the Jungfern Sill. The depth of the Jungfern Sill is indicated by the horizontal dashed line.

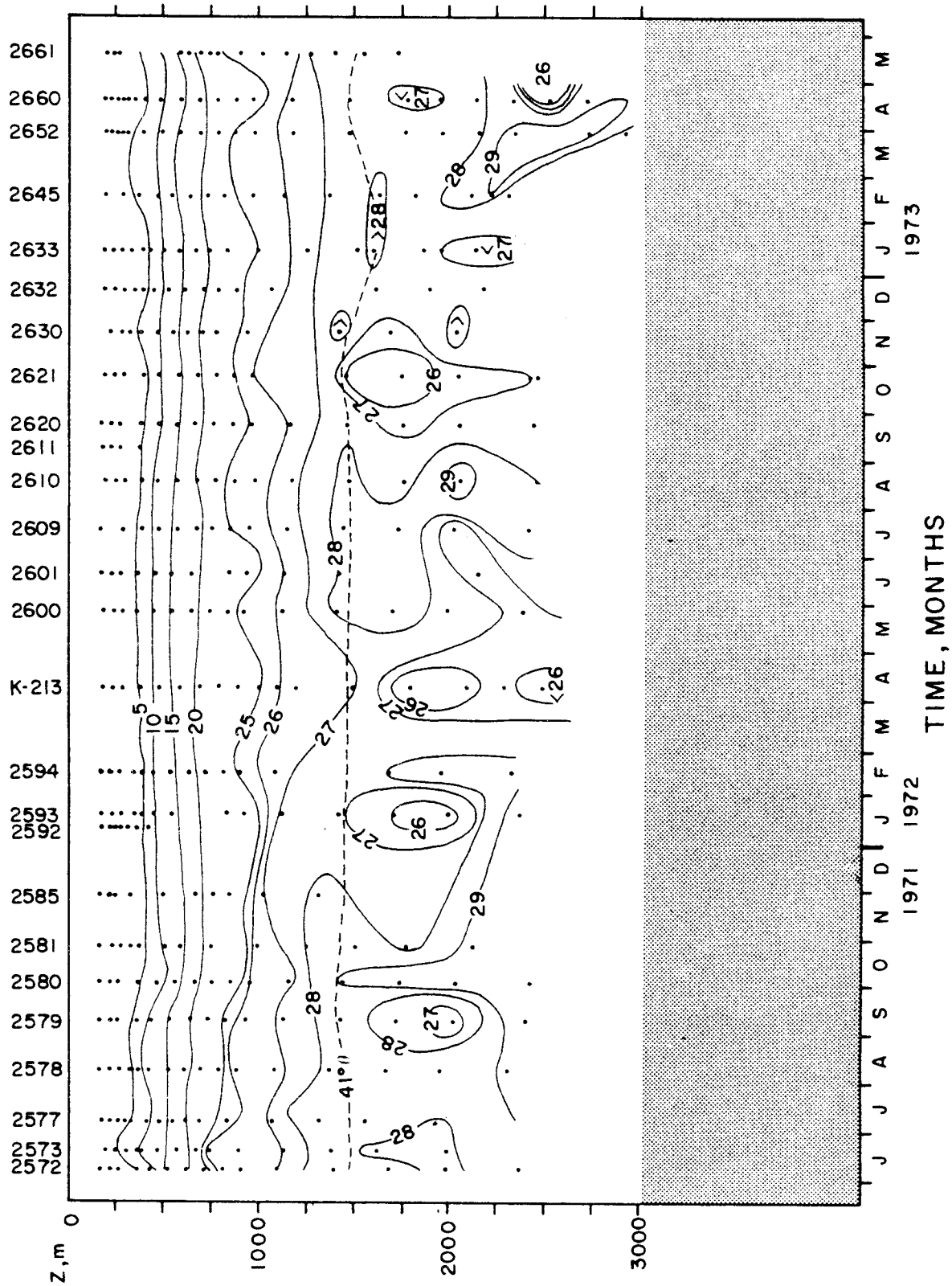


Fig. 7 Results of a two-year temporal study of dissolved silicate concentrations at the University of Puerto Rico PESCA Serial Station (17°36'N and 67°00'W).

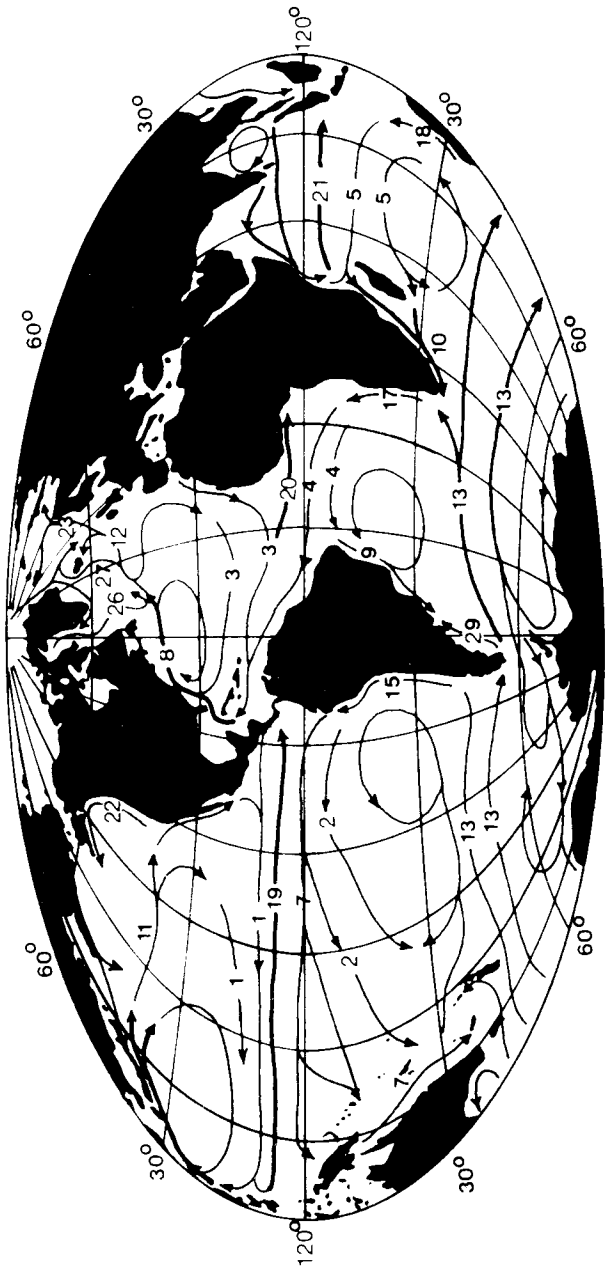


Fig. 8 Diagram of the surface circulation pattern of the oceans (after Dietrich, 1963). The names of major currents are given in the Table next to this figure according to the numbers in the figure.

Table 2

KEY TO THE CURRENTS SHOWN IN FIGURE 8

1 - 5	NORTH AND SOUTH EQUATORIAL CURRENTS	16	CANARY CURRENT
6	KUROSHIO	17	BENGUELA CURRENT
7	EAST AUSTRALIA CURRENT	18	WEST AUSTRALIA CURRENT
8	GULF STREAM	19 - 21	EQUATORIAL COUNTERCURRENTS
9	BRAZIL CURRENT	22	ALASKAN and ALEUTIAN CURRENTS
10	AGULHAS CURRENT	23	NORWEGIAN CURRENT
11	NORTH PACIFIC CURRENT	24	WEST SPITZBERGEN CURRENT
12	NORTH ATLANTIC CURRENT	25	EAST GREENLAND CURRENT
13	ANTARCTIC CIRCUMPOLAR CURRENT	26	LABRADOR CURRENT
14	CALIFORNIA CURRENT	27	IRMINGER CURRENT
15	PERU CURRENT	28	OYA SHIO
		29	FALKLAND CURRENT

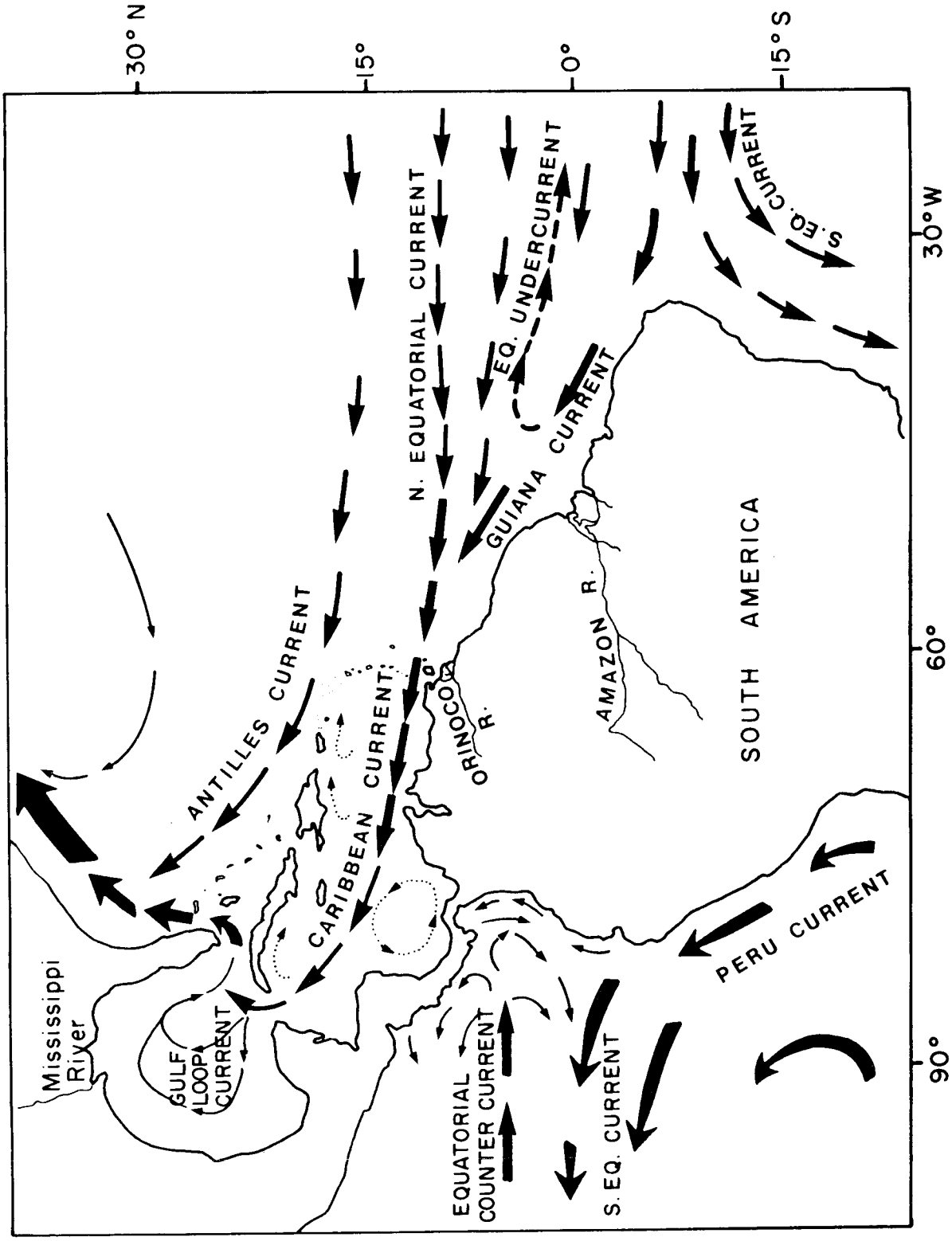


Fig. 9 Schematic representation of surface currents in and adjacent to the Caribbean Sea and Gulf of Mexico, as well as the northwest coast of South America.

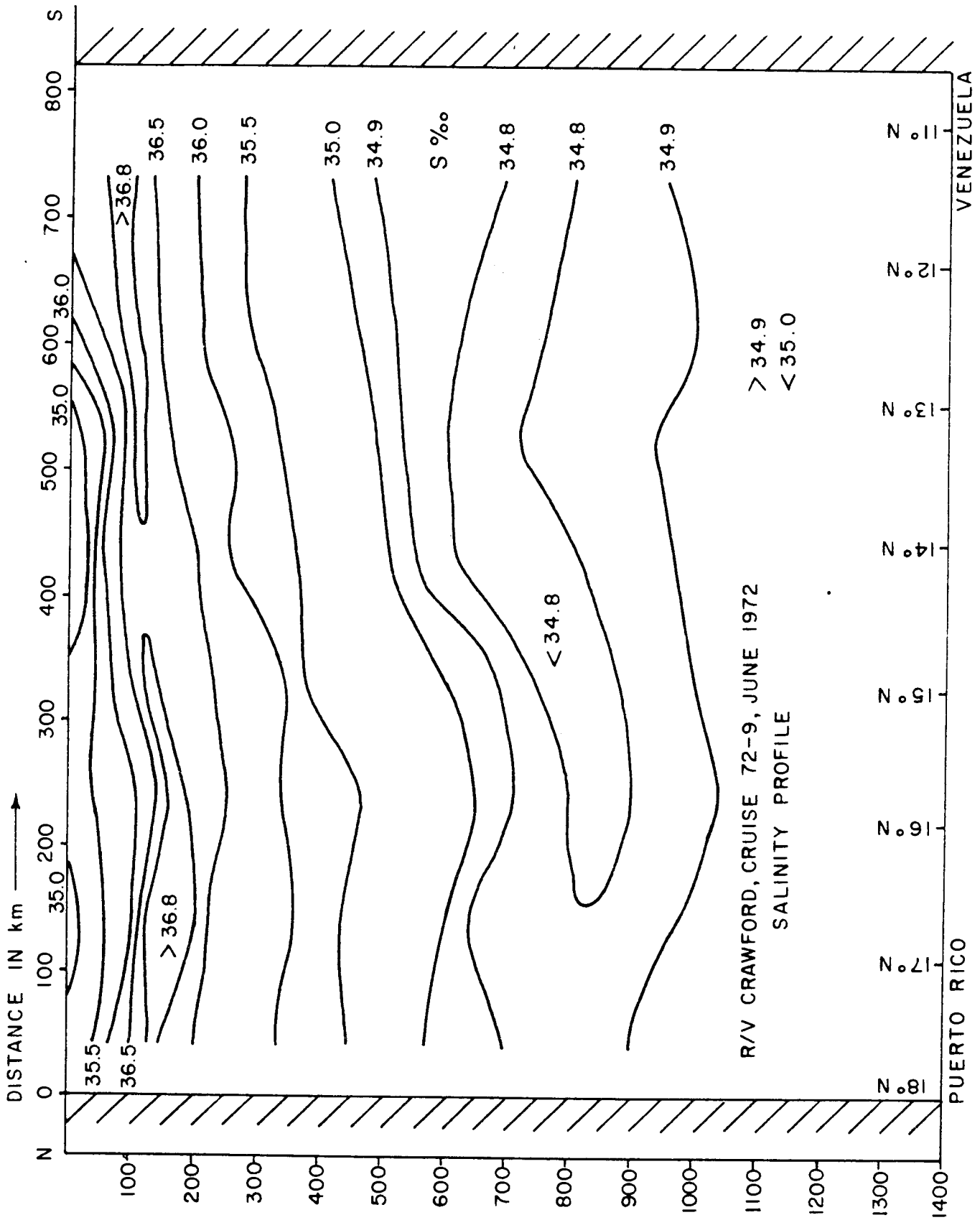


Fig. 10 Contours of salinity versus depth and latitude along 67°00'W from 18°00'N to 11°00'N. R/V CRAWFORD PESCA Cruise 72 - 9 June 1972, Stations 2601 to 2608.

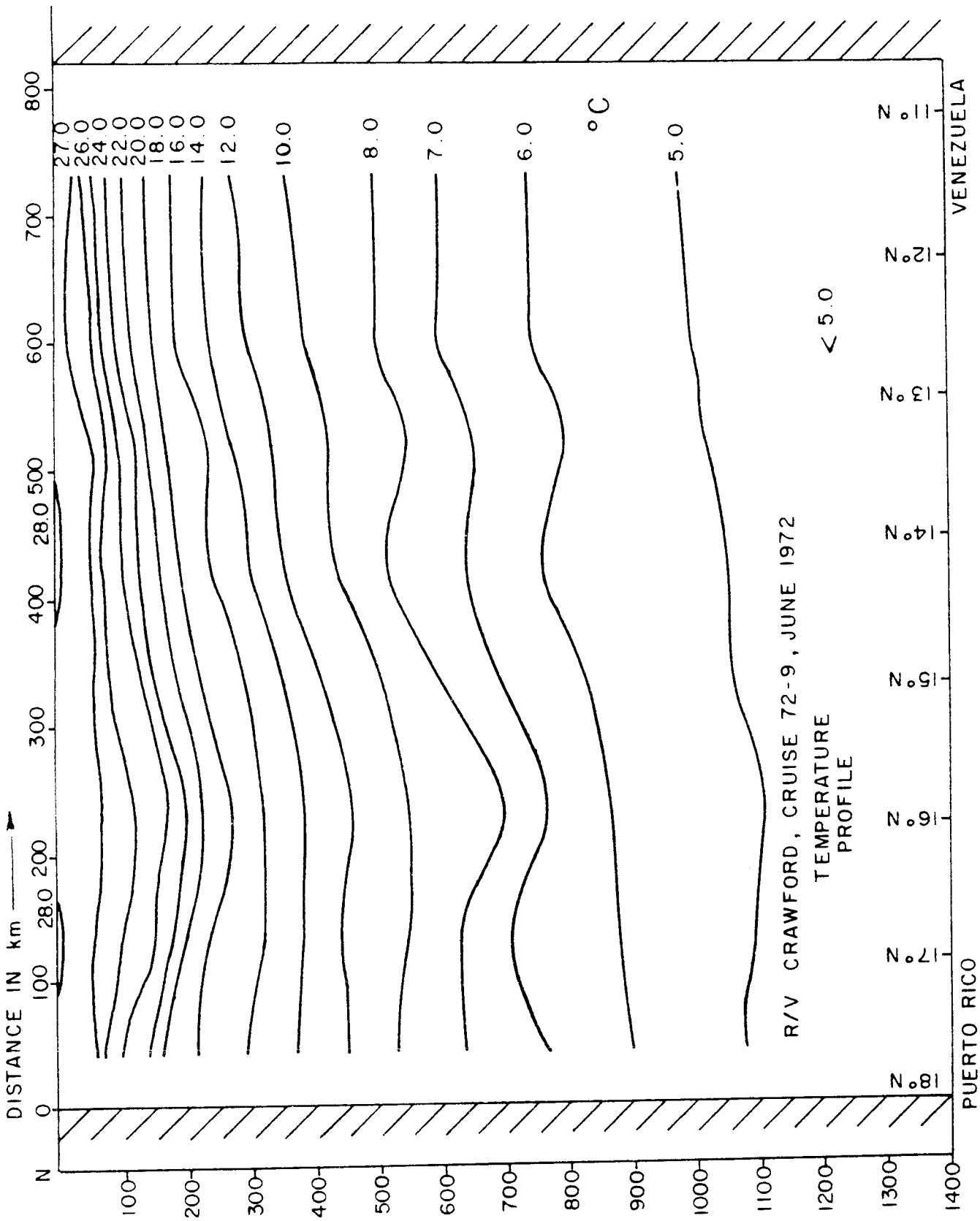


Fig. 11 Contours of temperature versus depth and latitude along 67°00'W from 18°00'N to 11°00'N. R/V CRAWFORD PESCA Cruise 72 - 9 June 1972, Stations 2601 to 2608.

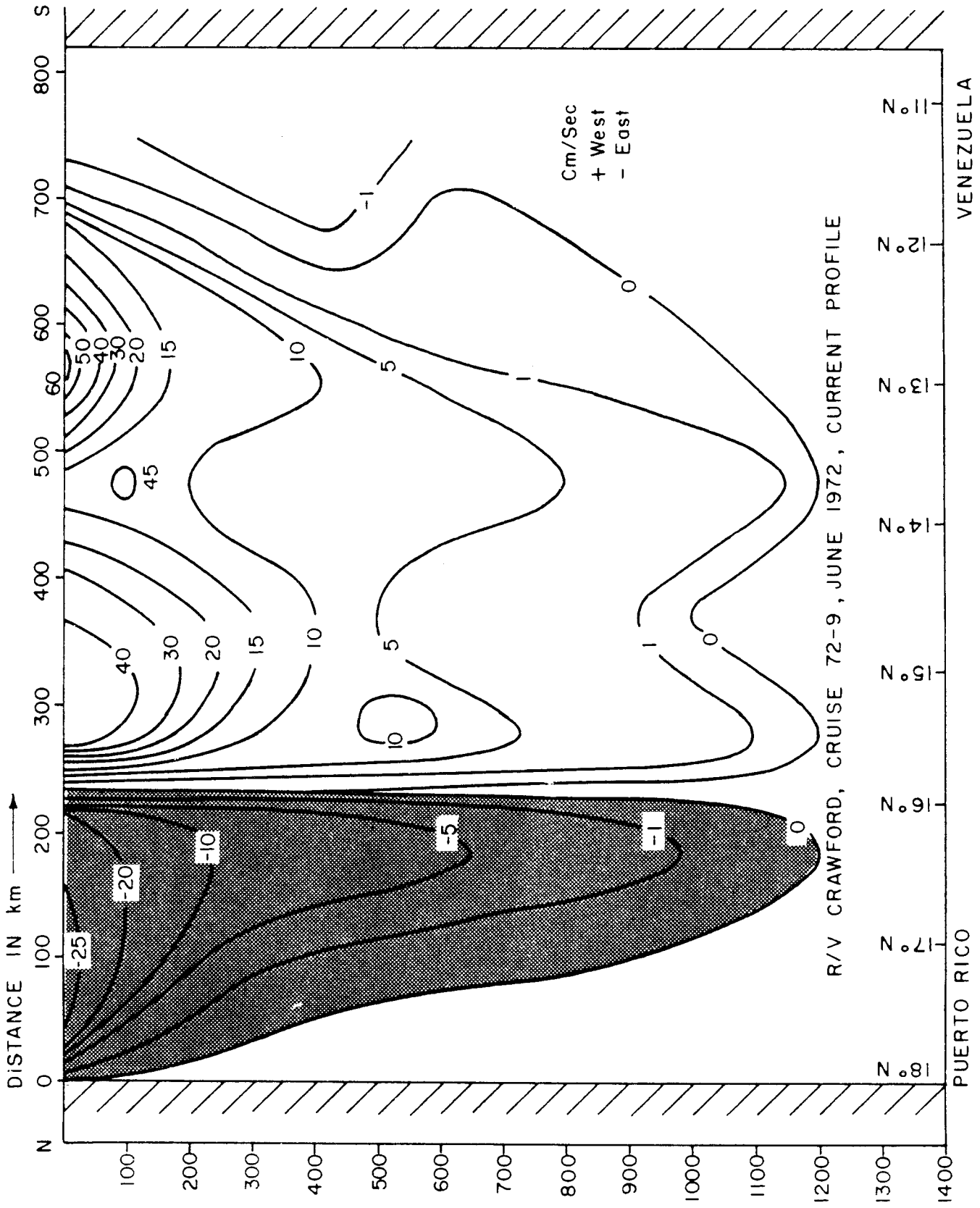


Fig. 12 Velocities along 67°00'W, determined by the dynamic method using salinity and temperature data depicted in Figs. 10 and 11. R/V CRAWFORD Cruise 72 - 9 June 1972, Stations 2601 to 2608. Velocities are in cm sec^{-1}. Positive values are westward flowing and negative ones are eastward flowing. Shaded areas are eastward flowing (into page).

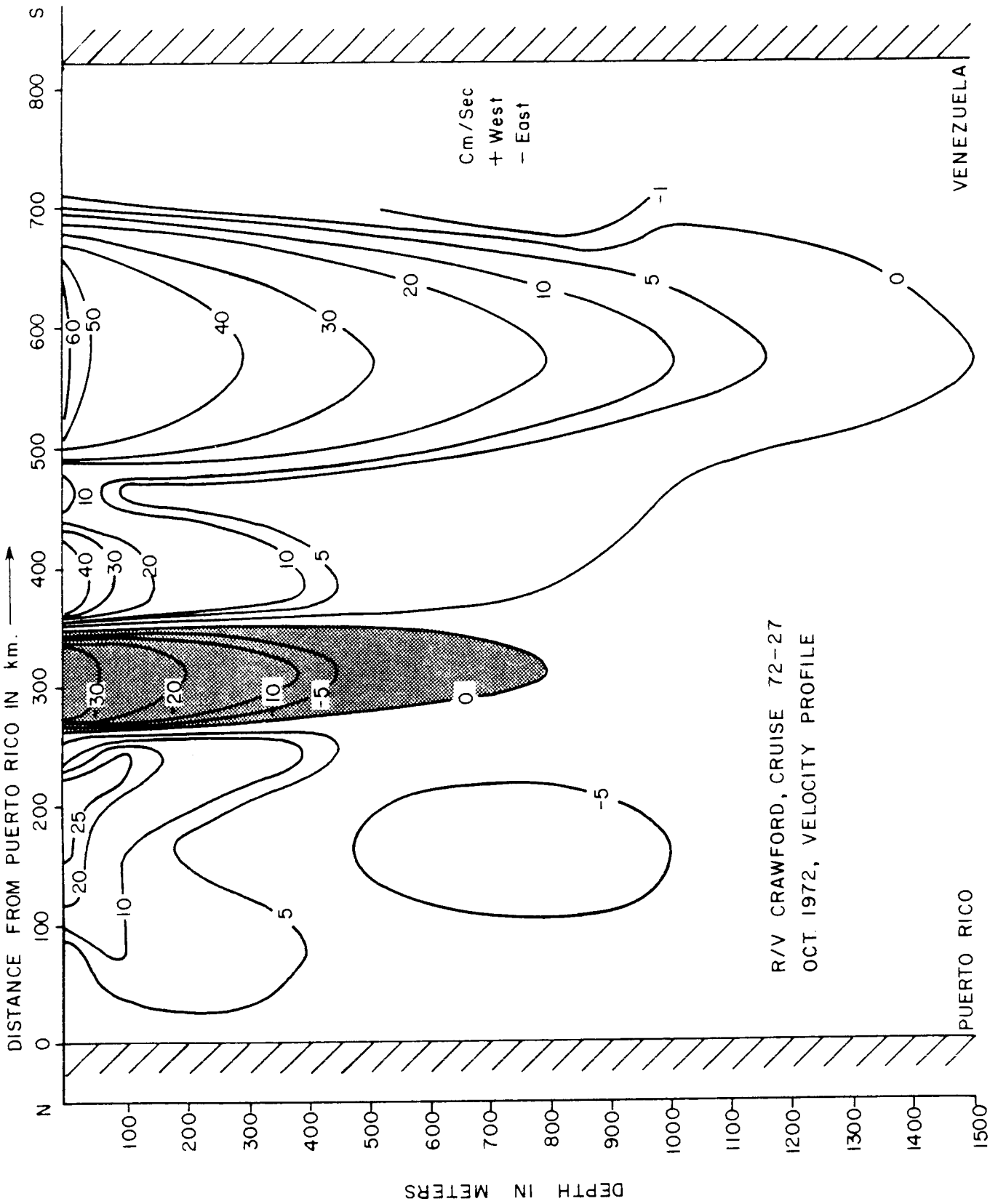


Fig. 13 Velocities along 67°00'W determined by the dynamic method in October 1972, R/V CRAWFORD Cruise 72-27, Stations 2621 to 2629. Velocities are in cm sec^{-1}. Positive values are westward flowing and negative ones are established eastward flowing. Shaded areas are eastward flowing (into page).

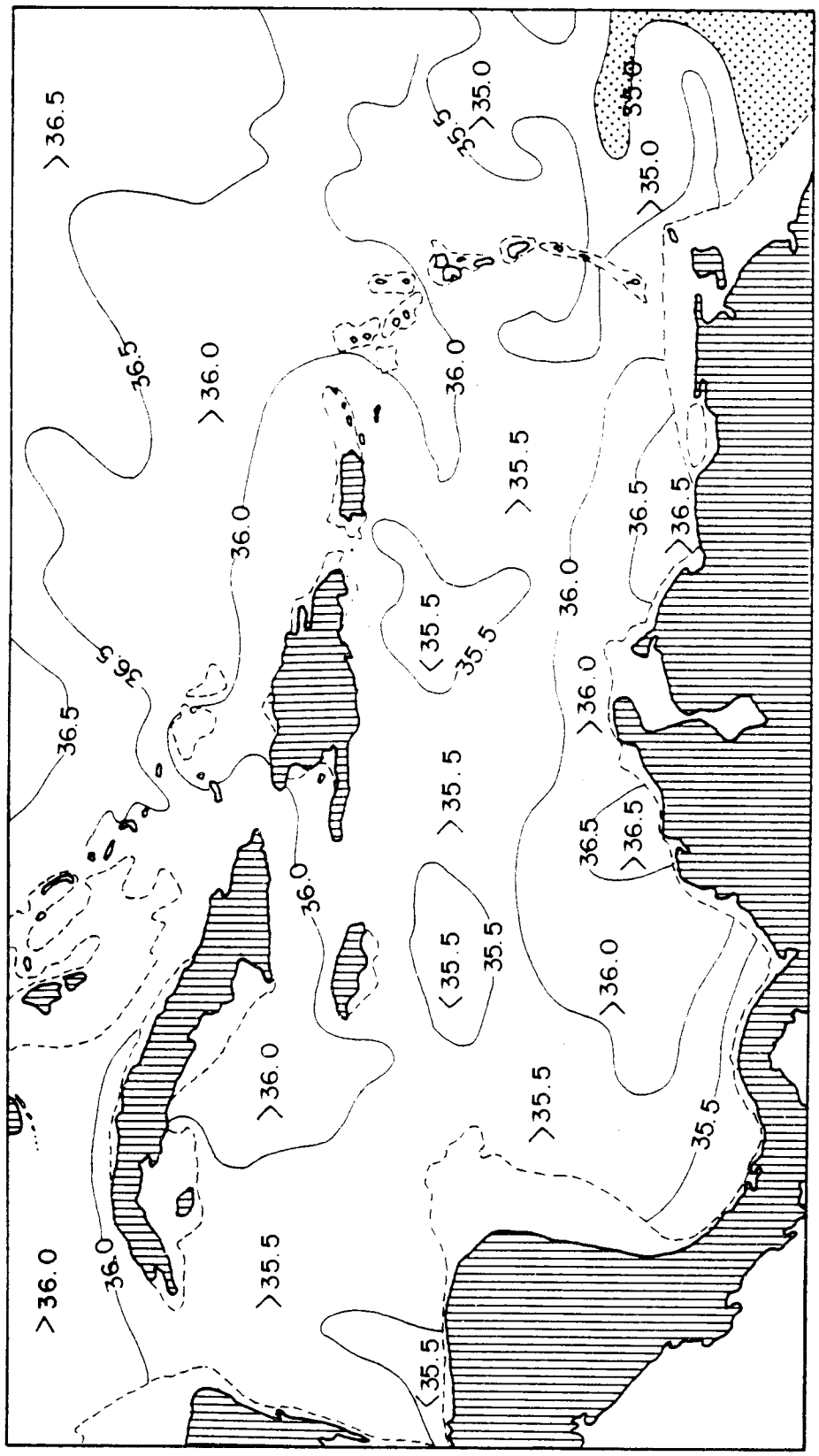


Fig. 14 Sea-surface contours of mean salinity in the Caribbean Sea between December and May (after Wüst, 1964).

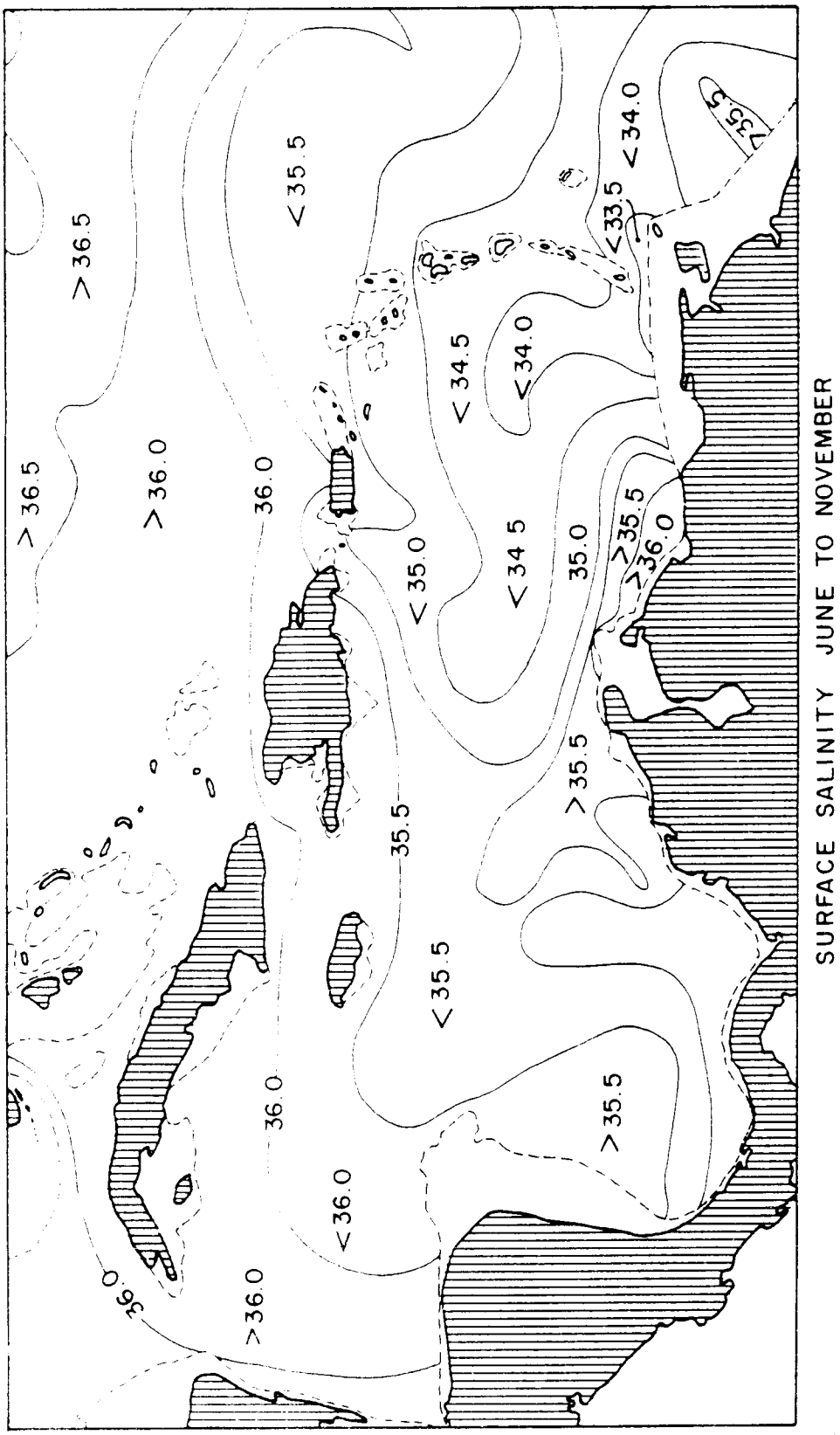


Fig. 14. Sea-surface contours of mean salinity in the Caribbean sea between June and November (after Wüst, 1964).

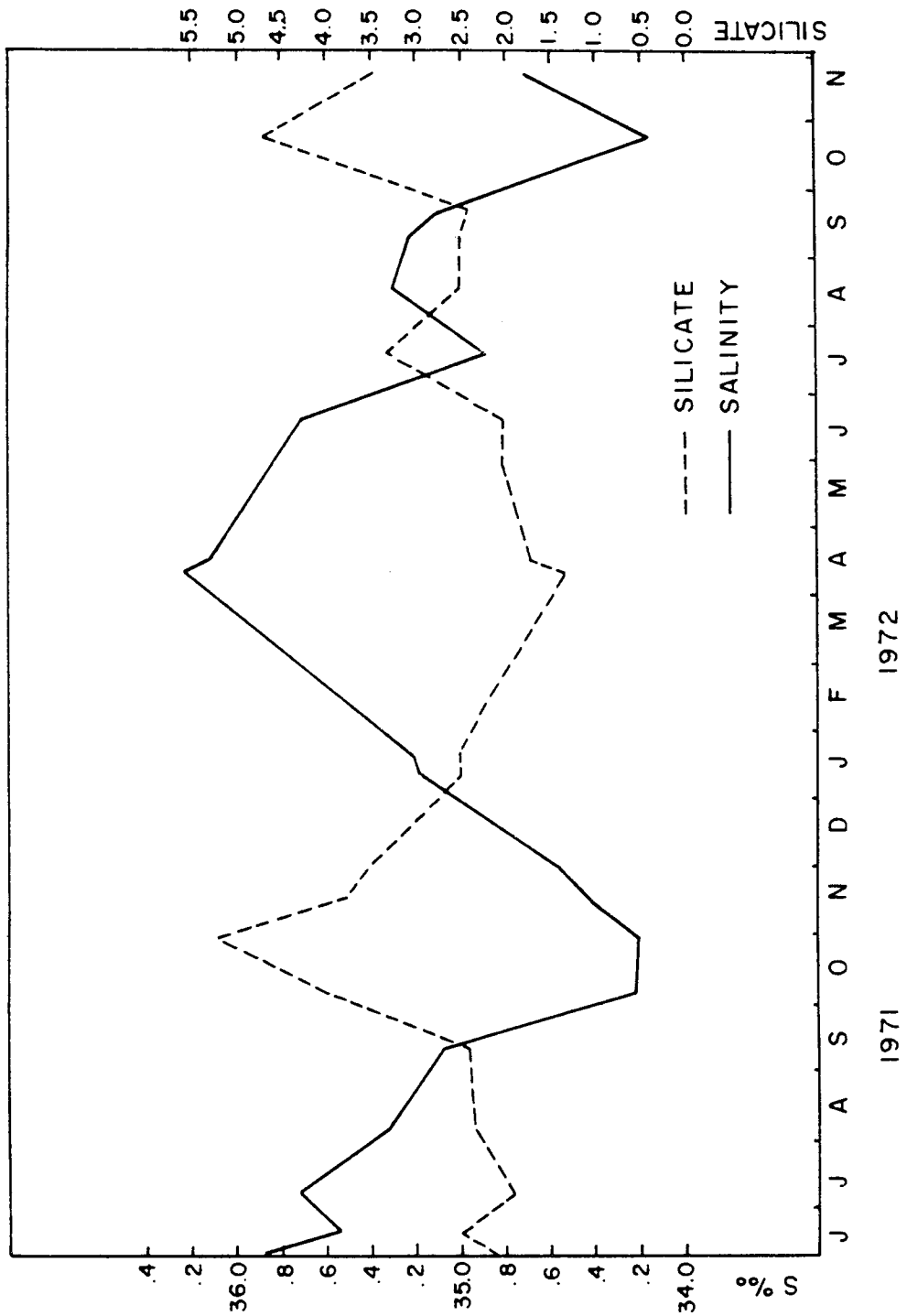


Fig. 16 Plots of dissolved silicate concentration and salinity for surface waters at the PESCA Serial Station for 1971 and 1972 at 17°36'N and 67°00'W.

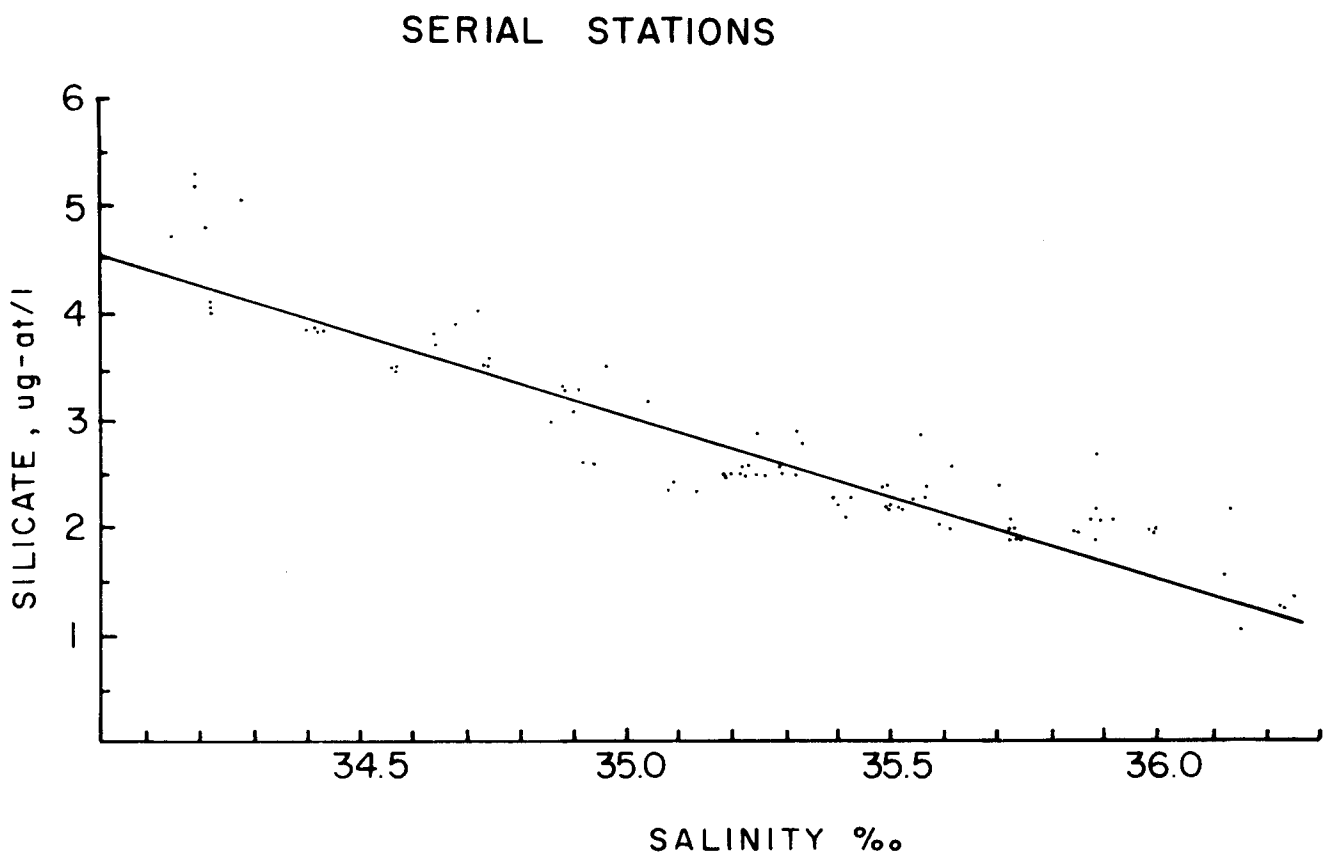


Fig. 17 Plot of dissolved silica concentration against salinity for surface waters at PPSCA Serial Station (17°36'N and 67°00'W) in 1971 and 1972.

REGIONAL OCEANOGRAPHY AS IT RELATES TO PRESENT AND FUTURE POLLUTION PROBLEMS AND LIVING RESOURCES - GULF OF MEXICO

by I. Emilsson

CONTENTS

1. Introduction

When compared with other maritime regions near populated areas of highly developed technology, our knowledge of the waters of the Gulf of Mexico could be qualified as reasonable in many ways. The first comprehensive study of the oceanography of the Gulf was made by Parr (1935) based largely on data gathered by the "Mabel Taylor" Expedition in 1932 and the "Atlantis" cruise of 1934. From then on the oceanographic investigations of the Gulf have progressed at an ever-increasing rate, especially in the post-war years, as a consequence of the general interest in ocean sciences and the expansion of the marine science institutions in the Gulf region.

In recent years these efforts have culminated in the field operations carried out through the international venture known as the IOC's Co-operative Investigations of the Caribbean and Adjacent Regions (CICAR). With the purpose of co-ordinating their efforts in space as well as in time, the CICAR member states have, since 1971, made observations along pre-established standard oceanographic sections and during previously agreed periods: the so-called CICAR Survey Months. By this system a synoptic or quasi-synoptic coverage of extensive areas within the Gulf has been obtained for the first time.

The results of these investigations were given at the CICAR-II Symposium, 12-16 July 1976, Caracas, Venezuela, where new discoveries were presented, many of which are of fundamental importance to our understanding of the circulation and water exchange in the Gulf of Mexico and adjacent areas. A volume of abstracts has already been published (Stewart, 1976) and the Proceedings of the Symposium will soon be published jointly by Unesco and FAO. Besides older sources, these recent findings have been used in the elaboration of the present report.

Thanks to the intensive work of oceanographic institutions in the United States of America, in particular those in Texas and Florida, our knowledge regarding the water movement in the entrance area and the eastern part of the Gulf has been greatly increased. The western and southwestern parts of the Gulf have also been subject to systematic studies in recent years thanks to the work carried out by Mexican institutions as well as those of the USA and USSR. Through these investigations our understanding of the water exchange between the eastern and western Gulf has received a strong impetus, although this central aspect of the Gulf oceanography still remains rather obscure.

Regarding the theoretical studies of the circulation, attempts have been made to account for the observed phenomena by means of mathematical models, like those of Paskausky and Reid (1972) and Wert and Reid (1972). Physical models such as the one presented by Ichiye (1972) have also been constructed. Such models fairly represent the observed circulation patterns, but owing to the complexity of the dynamics of the Gulf waters, that is the interaction between the wind-induced, the geostrophic, and thermohaline and diffusive transports, many problems remain unsolved.

2. Dimensions and Configuration

The area of the Gulf of Mexico is about 1.5×10^6 km^2 with a water volume of 2.3×10^6 km^3 (Bialek, 1966). In this respect it is about 3/5 the

size of the European Mediterranean but with a similar average depth of 1,500 metres. The east-west dimension of the Gulf is about 1,600 km which is 2/7 that of the Atlantic Ocean at similar latitudes. The western part of the Gulf has a north-south extension of 1,300 km while its central and eastern portion has one of about 900 km.

The bathymetry of the Gulf is shown in Figure 1. The main basin of the Gulf is a cul-de-sac that extends from the Yucatan Channel, first north and north-east, then west and finally south. The basin has an average depth of 3,000 metres. It is connected to the Cayman Sea in the southeast through the Yucatan Channel with a sill depth near 2,000 m., and to the Atlantic through the Straits of Florida which have a sill depth of 800 metres. The basin is surrounded by three wide shelf areas: the West Florida Shelf, in the east, the Texas-Louisiana Shelf in the northwest and the Campeche Bank in the southeast. Near the extreme west and south end of the basin, off the east coast of Mexico, the continental shelf is very narrow.

The Gulf basin is often thought of as having two separate openings. It should however be borne in mind that, except for the surface layer down to 50 m. depth, all flow in, as well as out, must go through the passage nearly 180 nautical miles wide between the northeastern edge of the Campeche Bank and the southwestern corner of the West Florida Shelf.

Compared with the Caribbean Sea, the Gulf has a quite regular and clear-cut bottom configuration in general, however, while the Caribbean and the Cayman Seas may be looked upon as a channel with several openings, the Gulf of Mexico is a semi-closed area, with relatively narrow openings. In spite of this limited connection to the adjacent ocean areas, the Gulf waters at all depths are very similar to the Caribbean waters, as shown by their T-S characteristics and the high oxygen content of the deep waters, indicating a high rate of water exchange. No doubt this intense communication is due to the kinematic conditions at the entrance where the swift north-flowing Yucatan Current, after meandering, is forced eastwards into the Straits of Florida.

3. Horizontal Circulation

The classical circulation pattern is shown in Figures 2 and 3. The information in these maps is derived from navigation records of ships sailing in the Gulf over many years and presented on the pilot charts that are published regularly by the U.S. Naval Oceanographic Office. These maps show the north-flowing Yucatan Current spreading out in various directions; to the west over the Campeche Bank; northwards towards the Texas-Louisiana shelf and eastwards into the Straits of Florida. In the eastern central Gulf the Yucatan Current is shown to turn clockwise and then flow to the east and south-east towards the Straits of Florida. Large cyclonic gyres are indicated in the southwestern Gulf and the west Florida Shelf. The current speeds range from the peak of 1.5 knots (about 35 nautical miles per day) on the west side of the Yucatan Channel to about 0.2 knots (about 5 nautical miles per day) in different areas in the western Gulf. The maps show little difference between the summer and winter circulation patterns.

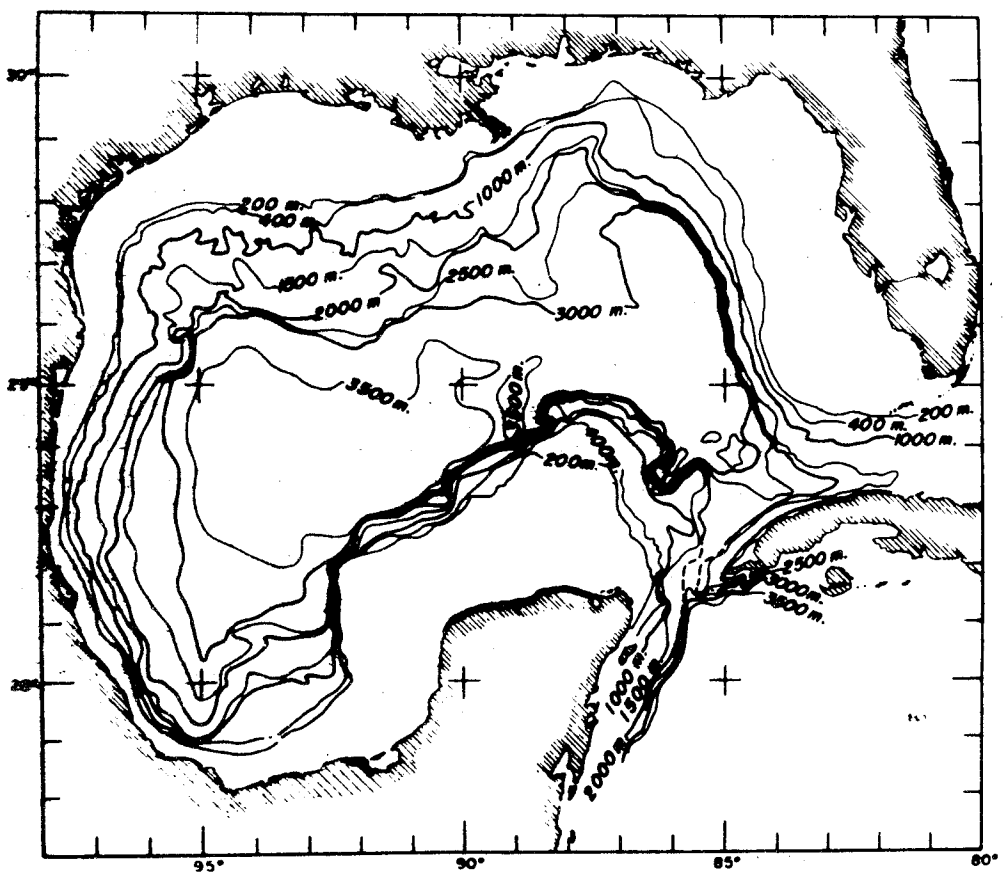


Fig. 1 Bathymetry of the Gulf of Mexico based on U.S. Coast and Geodetic Survey Chart 1007 and soundings on file at the Department of Oceanography, Texas A & M University. (from Nowlin, 1972.)

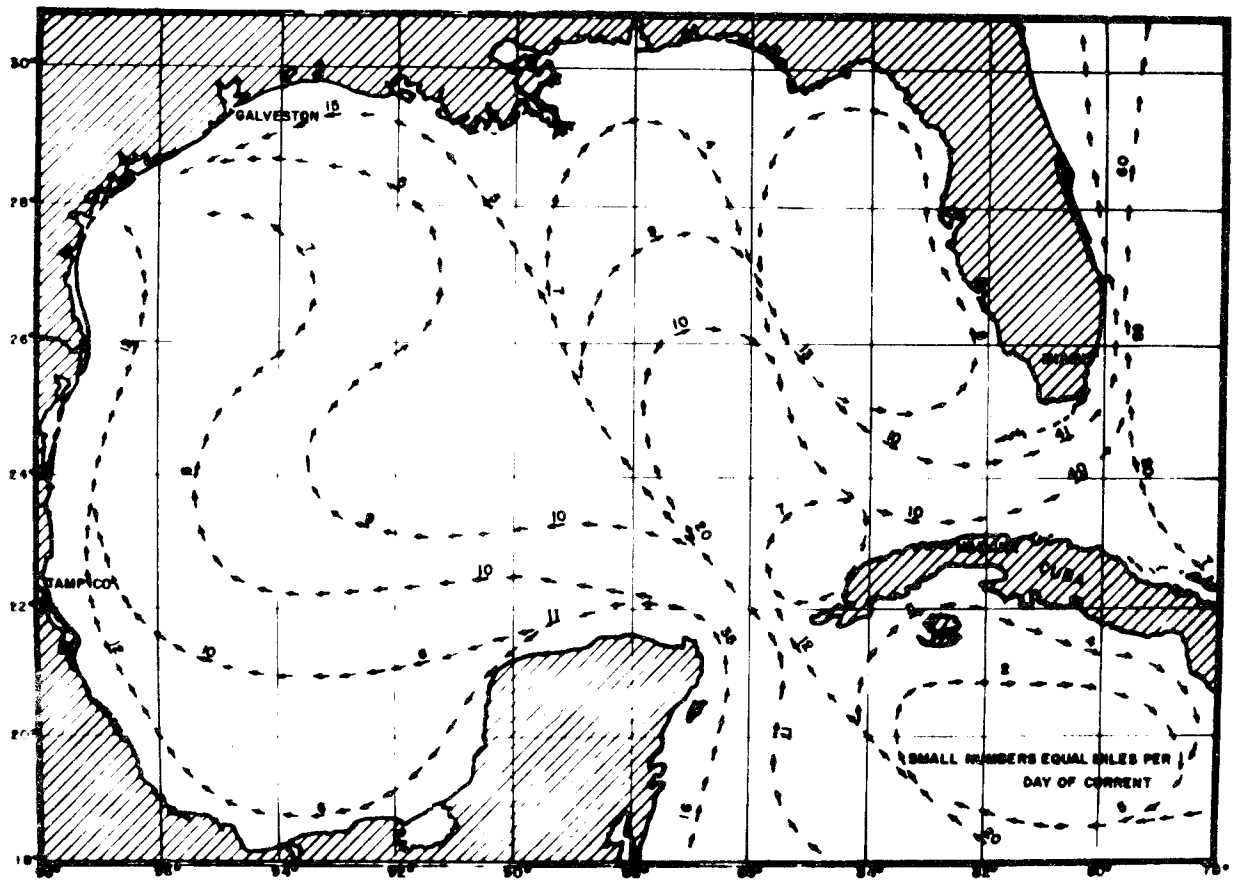


Fig. 2 Surface ocean currents in the Gulf of Mexico in June. (From Leipper, 1954.)

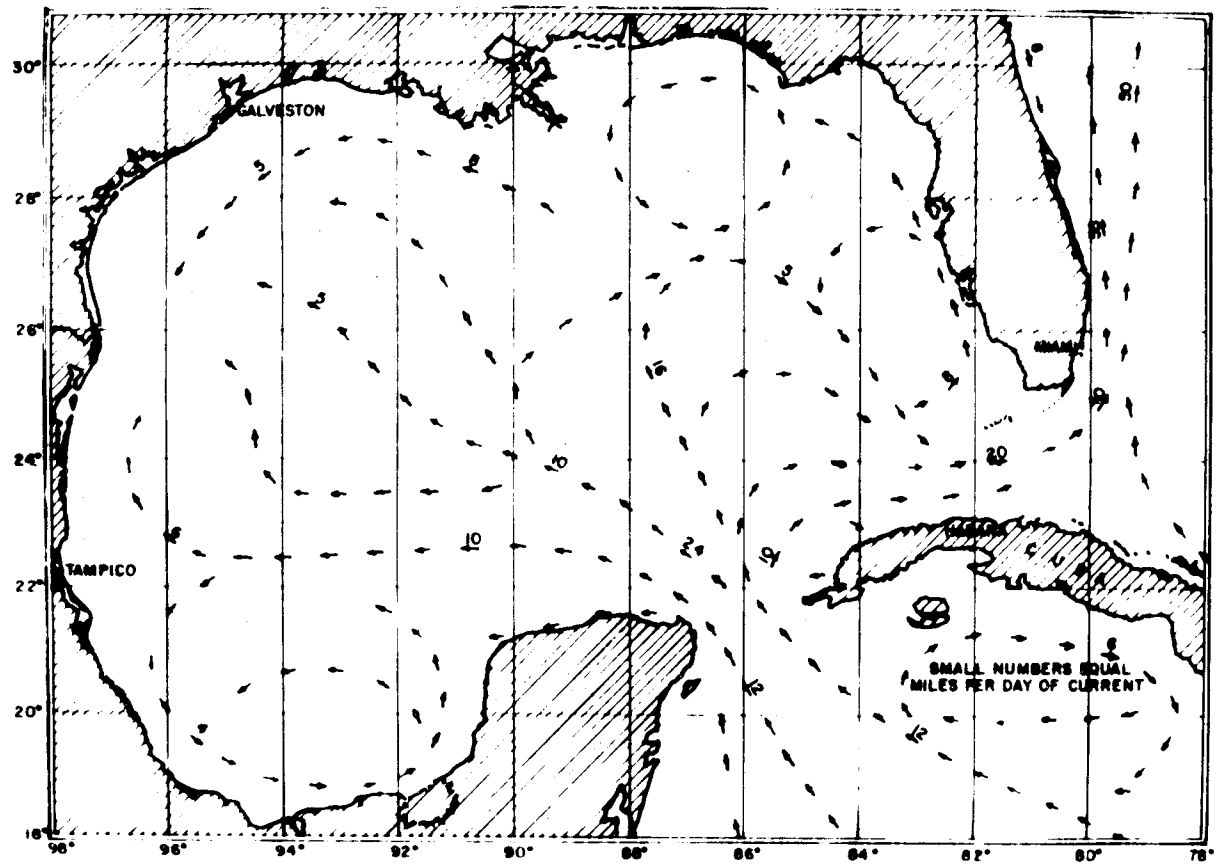


Fig. 3 Surface ocean currents in the Gulf of Mexico in December. (From Leipper, 1954.)

As Leipper (1954) has stated, there is probably no part of the world oceans of comparable size to that of the Gulf of Mexico where there is such a wide difference of opinion concerning the specific current regime. Sverdrup et al. (1942:641) state: "In the Gulf of Mexico several large eddies exist; and all of these appear to be semi-permanent features, the locations of which are determined by the contours of the coast and the configuration of the bottom." Considering the precarious data on which it was based, it is indeed remarkable that the studies during the 34 years since its publication have confirmed this statement by bringing out the evidence that there exists no such thing as stable climatological current patterns for the different seasons in the Gulf. It seems more likely now that certain recurrent features develop, move along and disappear in a long and varying chain of events. The investigations that pointed firmly in this direction were those conducted by the U.S. Fish and Wildlife vessel "Alaska" in the summer of 1951, providing the first complete oceanographic coverage of the Gulf (Austin, 1955). Figure 4 presents the dynamic topography of the sea surface relative to the 1,000 decibar surface. This map shows the Gulf filled with "highs" and "lows" in an apparently random fashion and when it was first published many believed that this confused pattern was simply due to the fact that the three cruises that were needed to cover the whole area by a single vessel over the period from April 22 to August 21, were too large for a synoptic representation. Later studies have shown, however, that the appearance of such highs and lows, and their displacement in a more or less random fashion within a certain range of variability, is the rule for the central and the western parts of the Gulf of Mexico. Assuming geostrophic equilibrium, the contours of the dynamic topography represent the lines and direction of flow, as indicated on the maps. The validity of this assumption in the case of such topographically confined areas as the Gulf may be disputed, but current observations by the G.E.K. and other methods are in agreement with the dynamic topography, at least as regards the direction of the flow.

3.1 The eastern Gulf

The dominating feature of the dynamic topography shown in Figure 4 is the "high" with closely spaced contour lines situated to the northeast of the Yucatan Channel. This topographic feature reflects the Yucatan Current and the anticyclonic loop that issues into the Florida Straits. As Nowlin and McLellan (1967) and other authors have pointed out, this loop is the primary current in the Gulf of Mexico, and is now usually referred to as the Loop Current. Besides its effects on the dynamic topography, the presence of the Loop Current is also revealed by the temperature distribution and it has been shown by Leipper (1970) and others that the topography of any isothermal surfaces between about 10° and 22°C is a good indicator of the geostrophic current regime in the eastern Gulf.

The position and extension of the Loop Current is highly variable. On several occasions a large anticyclonic eddy, some 200 km in diameter, has been observed to separate from its northern portion and move westwards. Leipper (1970) has proposed an annual cycle for the Loop Current. He finds that the current path advances northwards during spring; then, during summer and autumn, it spreads westwards to form an anticyclonic eddy before it recedes to a minimum extension during winter. A similar annual cycle has been found by

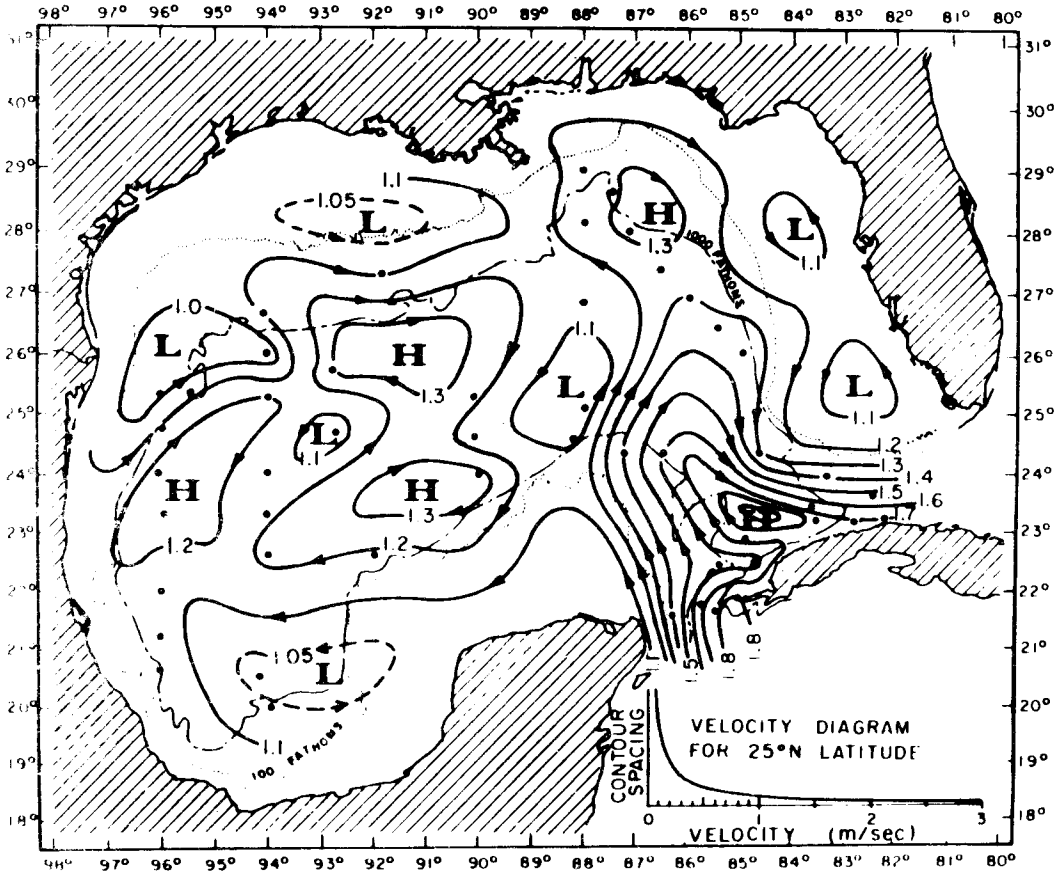


Fig. 4 Dynamic topography of surface relative to 1,000 decibar surface, Alaska cruises 1-1A, 2-1B and 3-1C, 22 April - 21 August 1951. (After Austin, 1955, reproduced here from Nowlin, 1972.)

Molinari (1976) by using the climatological temperature data compiled by Robinson (1973). The monthly position of the current axis as found by Molinari (op. cit.) is shown in Figure 5. Recent investigations have shown, however, that such a climatological cycle is marked by a random variability from one year to another. For example, in agreement with the proposed annual cycle, the Loop Current extended far into the Gulf during July-August 1971, as shown by the topography of the 20°C isotherm in Figure 6. On the other hand, in August 1975 the Loop Current had receded to a climatological winter position (Figure 7). Another example of such inter-annual variability is seen in Figure 8, when the northern portion of the Loop Current has given rise to a large anticyclonic ring already in April-May 1972, whereas in May-June 1975 the current path has advanced only moderately (Figure 9).

In the Yucatan Channel the core of the current is normally situated near the western border. During the summer a weak counter-movement is observed near the eastern side off Cuba. On some occasions, however, this counter-current has been observed to pick up strength and to occupy a wide portion of the channel.

In August 1971, during one of the Mexican CICAR Survey Month cruises, the present author (Emilsson, 1971) observed such a south-setting current which, at the speed of 0.5 knots, occupied the whole eastern half of the channel while the Yucatan Current was flowing at some 3 knots in a relatively narrow band near the edge of the Yucatan shelf. Nine months later we returned to this area only to find the normal situation with no vestiges of a counter-current, whatsoever.

Regarding the origin of such sporadic counter-movements, one may speculate on this relation to the Loop Current further to the north. As shown in Figure 6, in August 1971 the Loop Current was well developed and had apparently not lost any energy to a detached eddy, so that on its return southwards the central part of it might simply "overshoot" and, instead of turning towards the Florida Straits as it normally does, it had formed a large elongated gyre with its southern apex in the Cayman Sea.

Such a hypothesis receives a certain support from the principles of conservation of momentum and vorticity, but we should leave that question to the model-builders.

3.2 The central and western Gulf

It has been suggested that the large anticyclonic eddies that break off the northern portion of the Loop Current serve as a link between the circulation in the eastern and the western Gulf. According to Elliott (1976), these anticyclonic eddies affect the circulation at least to 1,000 m depth and carry some 100 x 10^{22} ergs of kinetic and potential energy derived from the feeder current. In this way the Gulf serves as an energy sink for the western boundary current in the North Atlantic. The anticyclonic eddies have been observed to move westwards at the rate of 50 nautical miles per month in the central area and slowing down to some 20 nautical miles per month as they advance into the western Gulf.

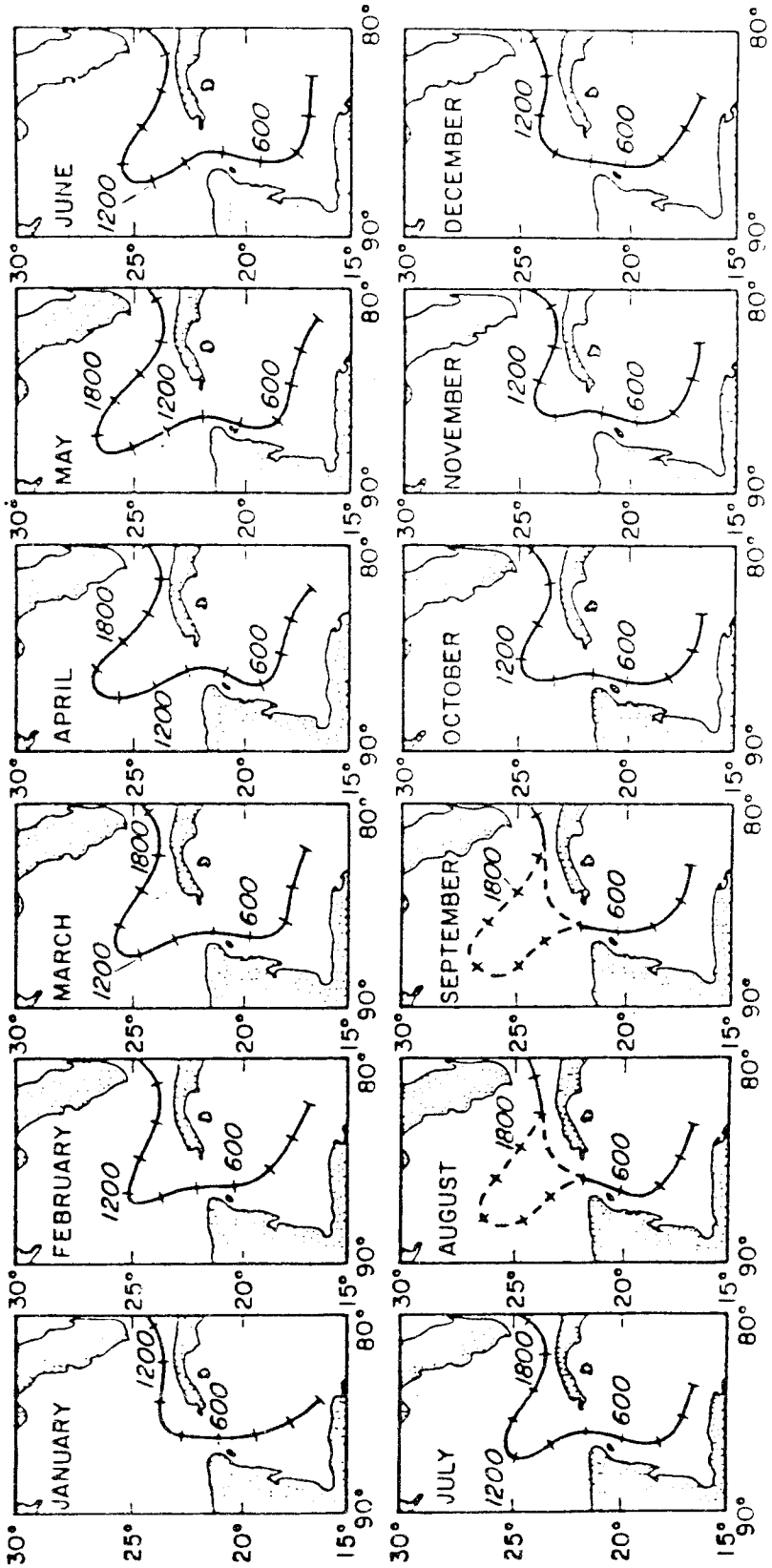


Fig. 5 Monthly mean axes of the Yucatan Current and the Loop Current as inferred from temperature distribution (After Molinari, 1976).

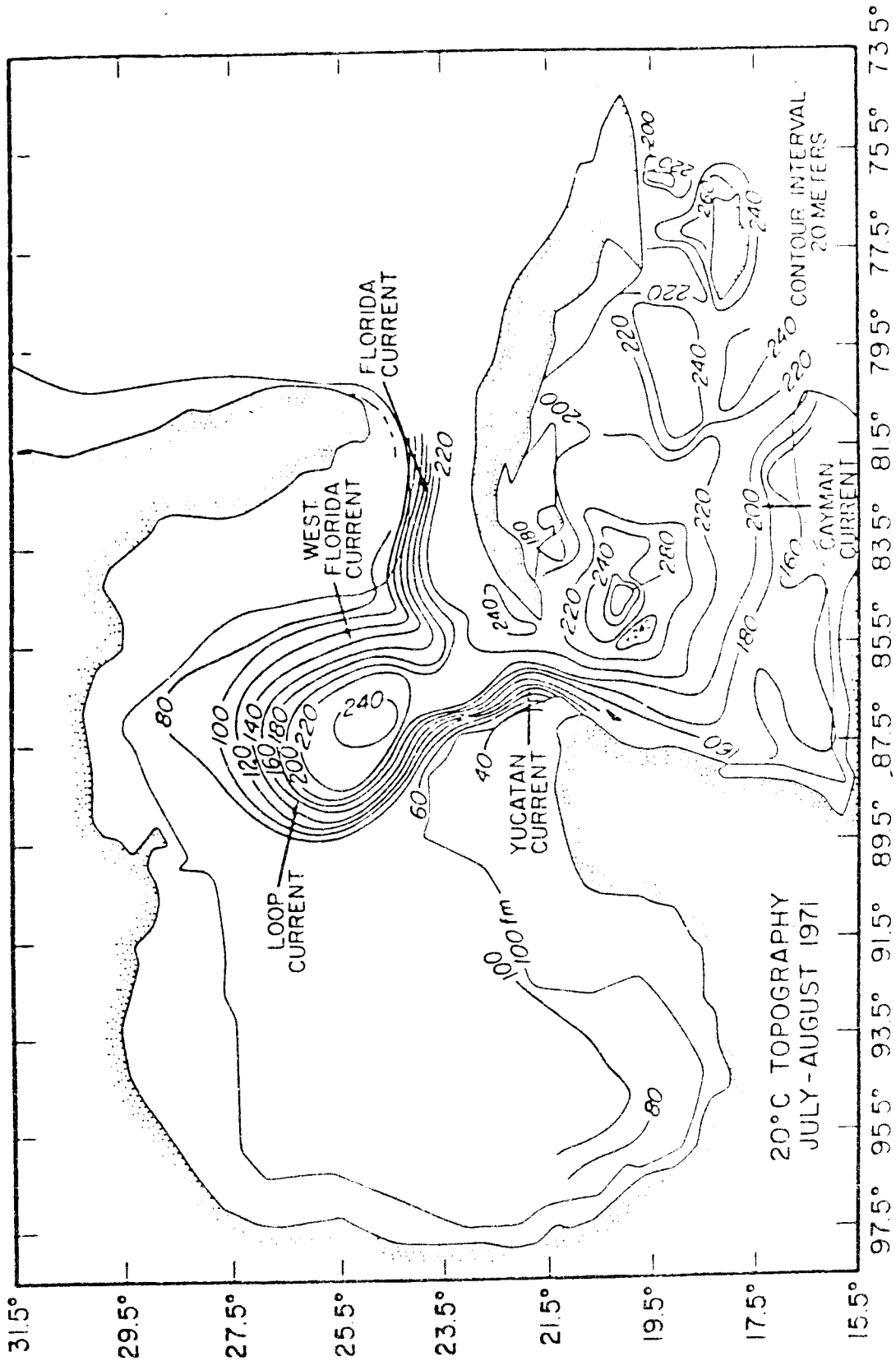


Fig. 6 The 20°C isotherm surface observed during CICAR Survey Month 1, July-August 1971. (After Molinari, 1976)

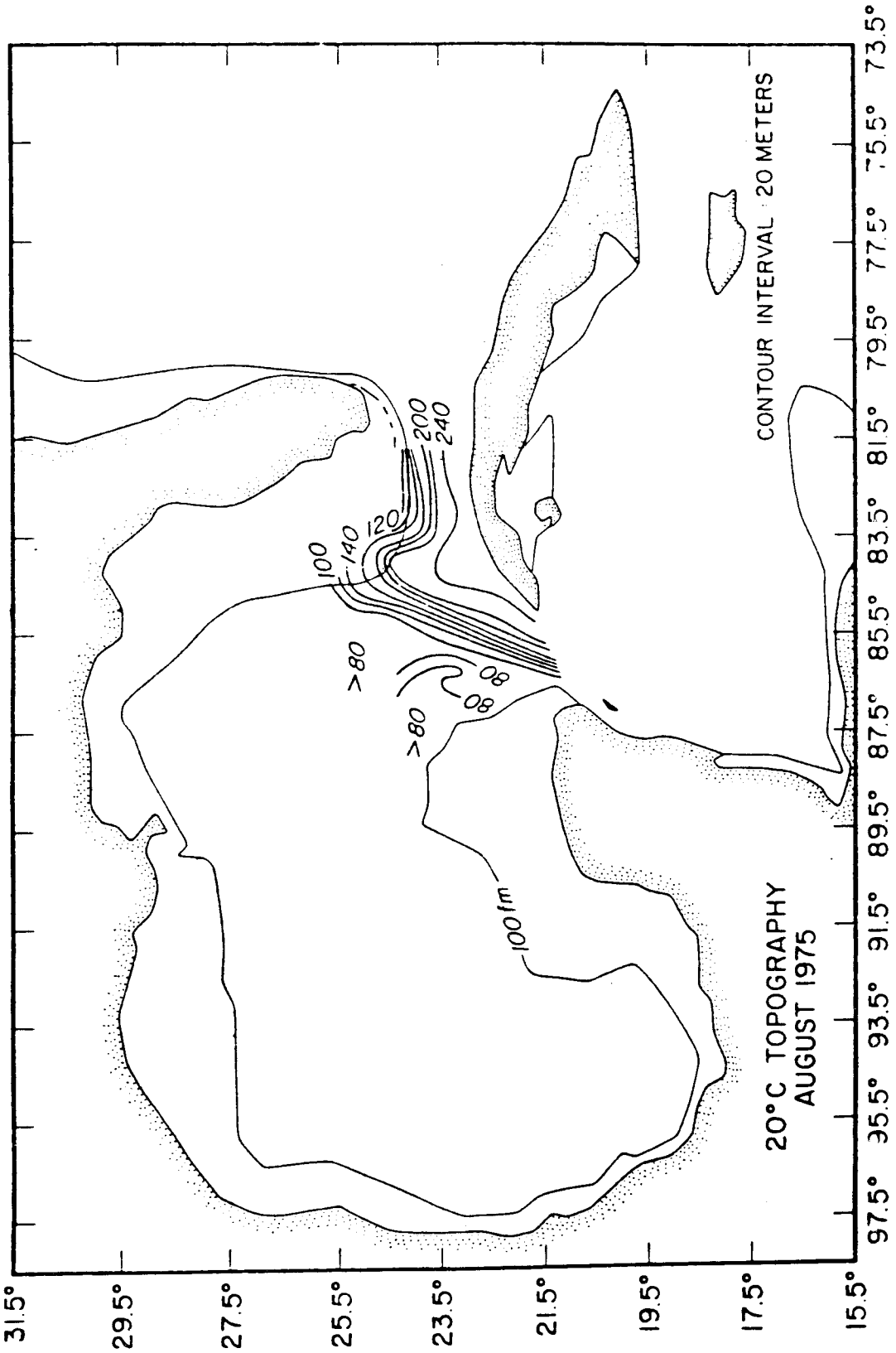
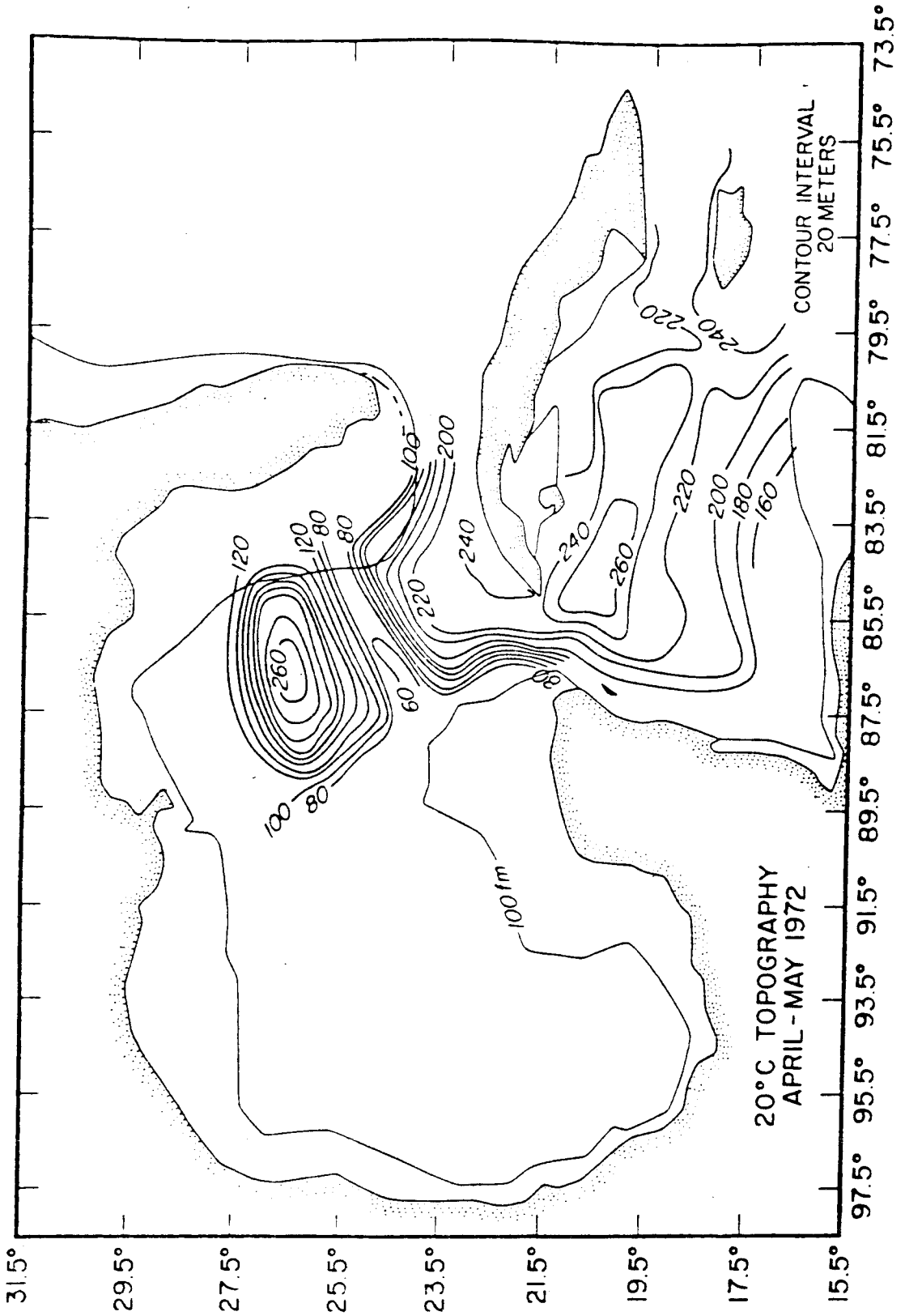


Fig. 7 The 20°C isotherm surface observed during August 1975. (After Molinari, 1976).



The 20°C isotherm surface observed during CICAR Survey Month II, April-May 1972. (After Molinari, 1976)

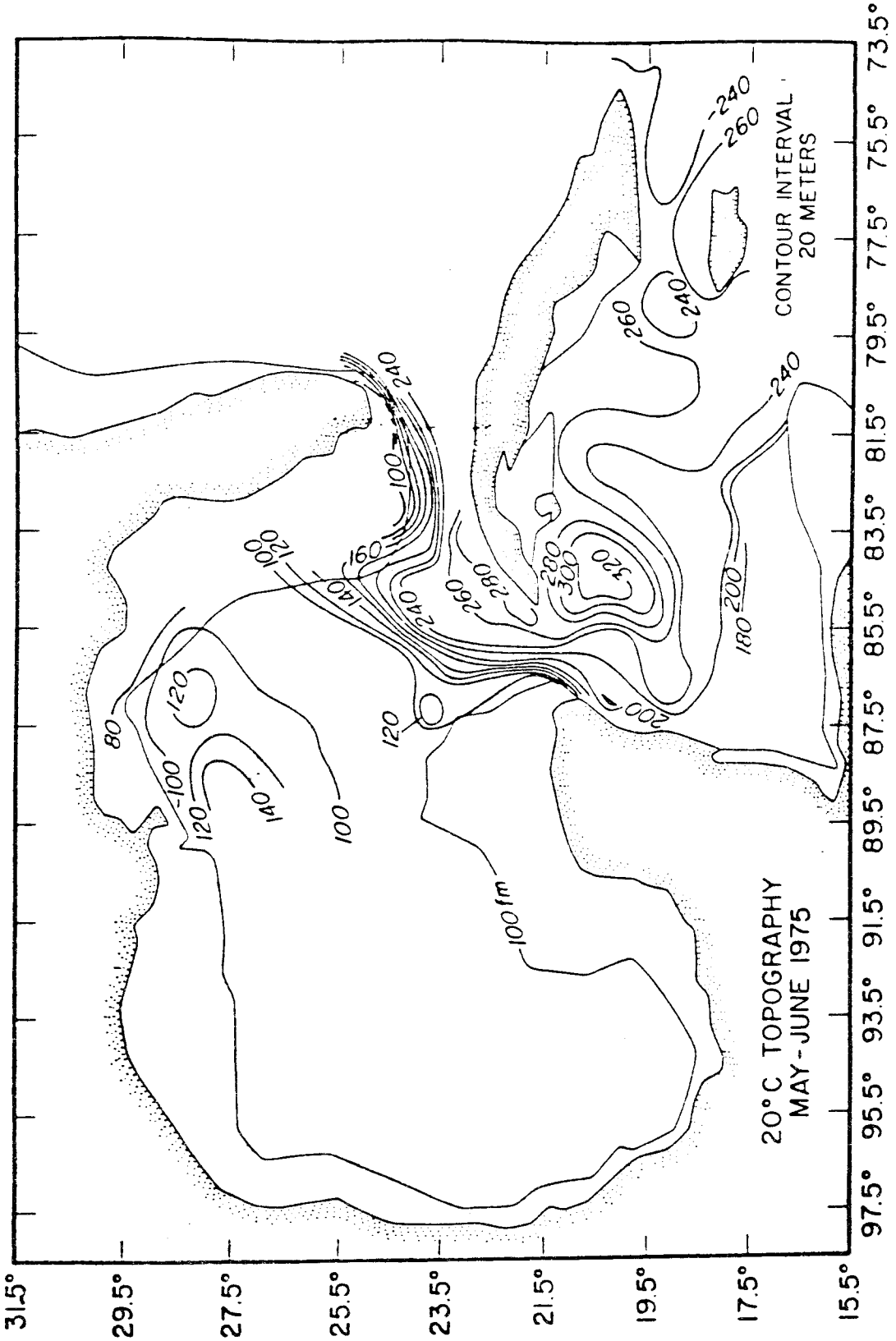


Fig. 9 The 20°C isotherm surface observed during May-June 1975. (After Molinari, 1976)

Vázquez (1974) has investigated the life history of such an eddy in the western Gulf on the basis of the Mexican CICAR data (Figure 10). He finds that the centre of the eddy moved from the central area towards the coast of Tamaulipas, Mexico, in one year at an average speed of 20 nautical miles per month. On approaching the coast the current velocity in the western sector of the eddy increased to 1 knot probably as a result of the reduced cross-section between the centre of the gyre and the shelf.

In the southwestern area of the Gulf a cyclonic gyre is apparently always present in one form or another, as shown in Figures 3, 4 and 10, but it does not always cover the entire Campeche Bay. In particular, on the extensive shelf area to the west of the Yucatan Peninsula a weak south-west current has been observed occasionally, probably in response to the wind stress.

Regarding the current velocity of the cyclonic gyre in the Campeche Bay, Emilsson and Mancilla (1976) have inferred from drift bottle experiments a period of approximately 100 days for a complete cycle, which corresponds to a drift velocity of some 10 nautical miles per day, or half a knot, on the average.

We have here presented evidence that the anticyclonic gyres hatched by the Loop Current play an important role in the circulation of the west Gulf by migrating westwards. Otherwise there seems to be little connection between the circulation regimes of the western and the eastern areas of the Gulf. Other factors being weak or absent, the wind stress, with its temporal and spatial variation, becomes the dominating one in the west.

3.3 A western boundary current in the Gulf of Mexico

It has been said that the Gulf is a water body large enough to behave like a mid-latitude ocean and yet small enough to serve as a natural laboratory. Taking advantage of this circumstance, Sturges and Blaha (1976) have recently compared the circulation in the western Gulf with that of the North Atlantic at similar latitudes and have postulated the existence of a western boundary current in the Gulf, a sort of miniature Gulf Stream system.

They found that many features of the observed density distribution and tidal heights in the Gulf of Mexico indicate that the Gulf contains a western boundary current and an interior flow field remarkably similar to the principal mid-latitude anticyclonic gyres.

They point out that the Gulf of Mexico is driven by a wind-stress curl similar to that of the central North Atlantic and that this current, analogous to the Gulf Stream, has a transport of at least 10×10^6 m^3 sec^{-1} (10 sverdrups). The curl of the wind-stress in the Gulf of Mexico is comparable with that of the winds driving the Gulf Stream system for six months of the year. As mentioned above (p.83) the east-west extension of the Gulf is about 2/7 the width of the Atlantic at the same latitude, hence the integrated transports will be reduced accordingly.

The response to the changes in the wind field seem to be fast and similar to what has been observed in the western Indian Ocean where the Somali Current responds to the onset of the Monsoon winds. Whether the north-

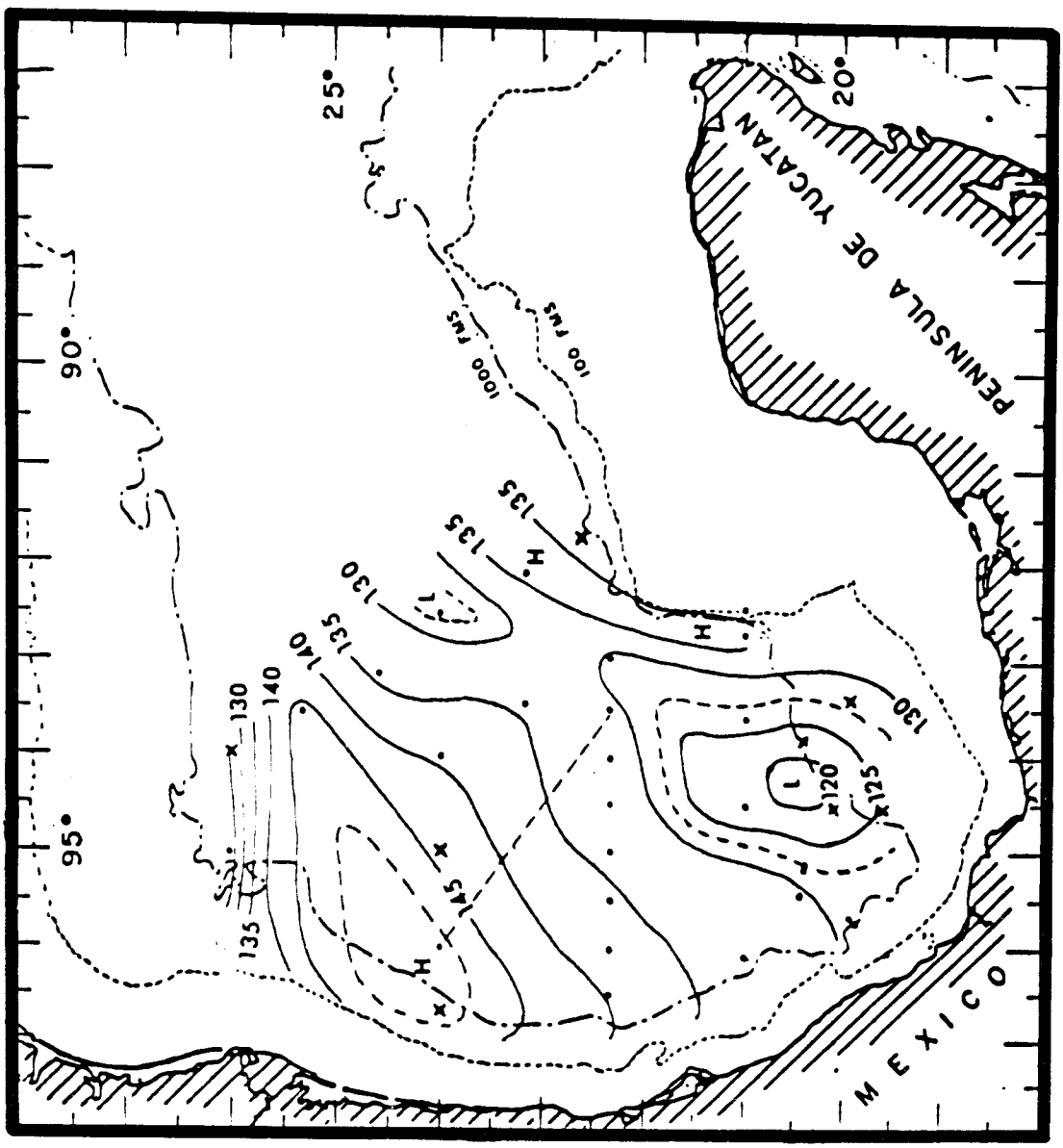


Fig. 10 Geopotential anomaly (in dynamic centimetres) of the sea surface relative to the 1,200 decibar surface. (After Vázquez, 1975)

flowing current in the western Gulf can be accounted for as a western boundary current remains to be investigated in greater detail.

3.4 The shelf and near-shore circulation and diffusion

Over the three wide and shallow shelf areas in the Gulf the wind stress is particularly important, and close to the shore it outweighs the coupling effect of the general circulation over the deep areas. Tidal currents are also of considerable consequence because, although the astronomical tidal ranges are small in the Gulf, the tidal currents are relatively strong over the outer fringes of the shelf areas owing to the great amounts of water that must pass across the shallow cross-section in order to cause the changes in sea level at the shore.

Entrainment and drag effects near the major river outlets are also of importance for the circulation off the adjacent shoreline, in particular during periods of intense discharge from the rivers. An example of such an effect has been reported by Emilsson et al. (1973) near the Panuco river outlet on the central Gulf coast of Mexico (City of Tampico). In this area the shelf is narrow and the offshore current sets to the north as part of the anticyclonic gyre (or the western boundary current). Close to the shore, however, to the north of the river mouth the water was moving steadily to the south towards the plume of the river during the 15-day period of observation. This example shows also that information on the circulation over the deep-water areas, when extrapolated into the near-shore zone, can be very misleading.

All along the shores of the Gulf there are many bays and lagoons which have relatively restricted outlets to the outer sea. In such channels the tidal currents may become quite strong particularly midway between high and low water. Under these circumstances, the tides, together with the run-off from surrounding land areas, maintain the flushing of the land-locked water body. During the dry season the tidal movement becomes the sole factor, and where the tide is diurnal and of low range its effects are too small to counter the littoral transport of sediments, with the result that the outlet closes, as is the case for many of the coastal lagoons on the coast of Tamaulipas, Mexico.

4. Vertical Advection and Mixing

4.1 The surface layer

The surface layer in the Gulf of Mexico is highly stratified, in particular in the western and central regions. Over the deep Gulf the mixed surface layer barely reaches 30 m in summer, whereas in winter it may increase to some 75 m. As a result of this stratification, a thin layer with super-saturated values of oxygen is often observed during spring and summer at depths of 30 to 50 m, just above the top of the oxygen-minimum layer. This supersaturation, produced by photosynthetic activity below the nutrient-poor and transparent surface waters, could not be maintained under the influence of active vertical mixing and advection. On the other hand, during the winter the reduction in temperature and increase in salinity by excessive

evaporation produce convection that deepens the mixed surface layer, with the result that the high-oxygen layer erodes and disappears, and some nutrients are brought to the surface.

Strong winds, like hurricanes and northerlies, produce vertical mixing, in particular when the static stability near the surface has been reduced by cooling. On the other hand, hurricanes tend to produce divergence in the surface layer accompanied by an ascent of the thermocline, with the result that the thickness of the mixed layer remains practically unchanged, with reduced temperature however.

The present author has observed a similar mechanism in the case of a strong northerly wind blowing over the western Gulf. Before the onset of the northerly there was a homogeneous surface layer 25 m thick with a temperature of 27.5°C. After the northerly, the homogeneous layer remained 25 m thick although the temperature fell to 26°C. At the same time the thermocline had ascended some 12 m.

Figure 11 shows the temperature (a) and the density (b) in the surface layer as a function of depth and time, in the southwestern Gulf (22°N-94°W) over a one-year period from 8 November 1970 to 3 November 1971, based on data obtained from the Mexican research vessel "Cadete Virgilio Uribe". On the occasion of the first cruise the homogeneous top layer had reached 50 m depth with a temperature about 26.5°C and a strong thermocline (the first northerly wind of the season had already passed some days before the observation). In January the temperature had fallen to 24.5°C but the thickness of the top layer had been reduced slightly or was practically unchanged, as a result of the ascent of the thermocline, in compensation for the horizontal divergence in the surface layer. On the other hand in spring, by the end of the season of northerly winds, the isotherms can be seen to spread out and the thermocline to weaken. Based on these and other criteria, Soviet oceanographers have constructed maps indicating vertical displacements in the upper 200 m in the Gulf of Mexico, as shown in Figure 12 (VNIRO, 1967).

In the shelf areas of the Gulf, vertical movements are also quite restricted. Near the large rivers the stability is increased by the outflow of fresh water. The vertical diffusivity is also reduced by the small vertical dimension. Over the wide and shallow bank to the west of the Yucatan Peninsula (Campeche), the salinity increases to 37-38°/oo during winter and spring owing to the excess of evaporation over precipitation and run-off, a situation which indeed prevails over the whole Gulf area in these seasons. The accumulation of such high-salinity water over the shelf indicates that the water exchange, by advection and diffusion, with the adjacent deep area is quite small. On the other hand, the salinity-induced increase in density of the shelf water may produce ephemeral sinking near the edge, to depths greater than that of the mixed top layer over the deep Gulf. Such processes have been shown to take place over the shallow platform that borders the south coast of Cuba in relation to the deep areas in the Cayman Sea (Emilsson et al., 1971).

4.2 The deep layers and the basin waters

The vertical thermohaline structure, as well as the distribution of dissolved oxygen, indicate that the water masses in the Gulf above the sill

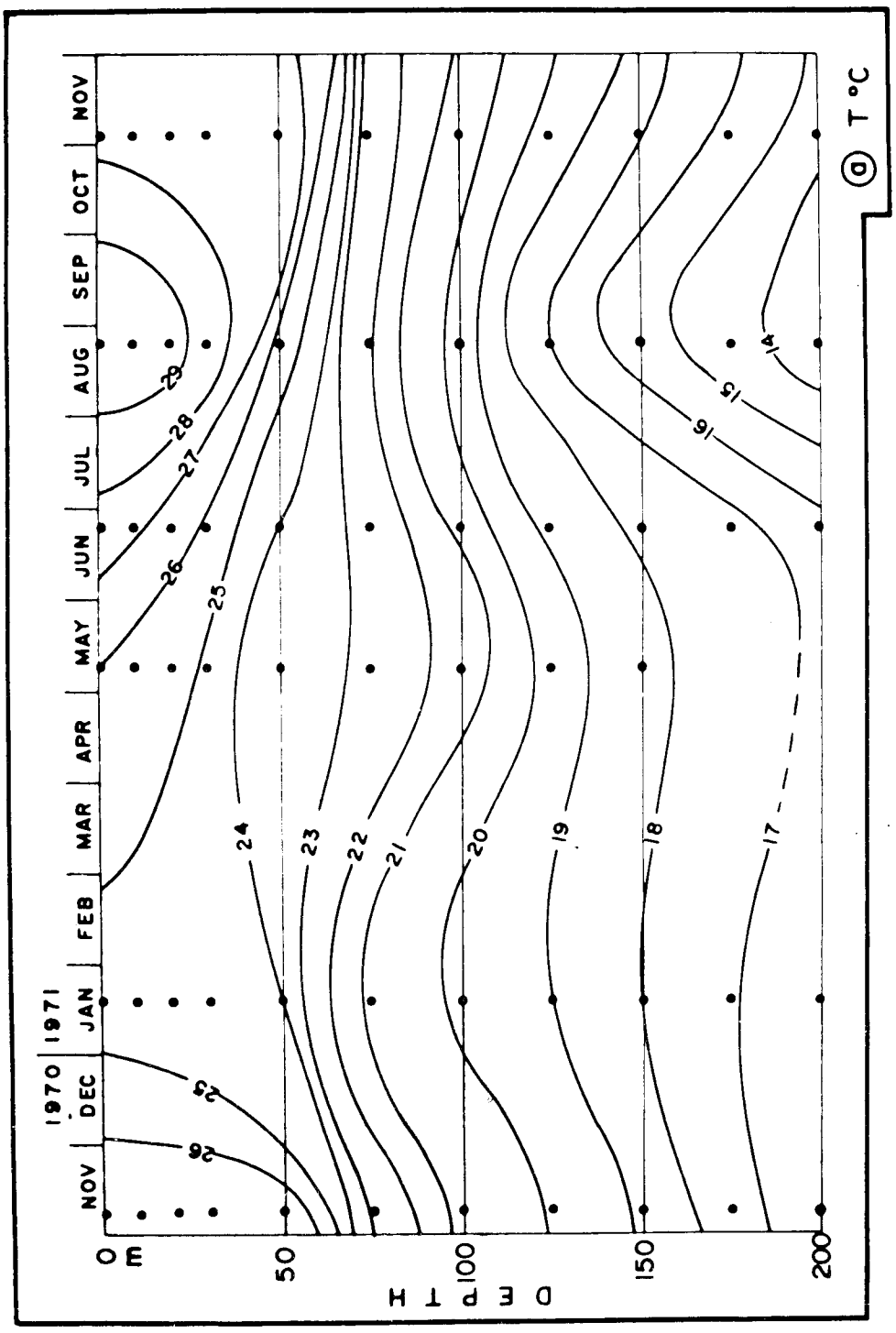


Fig. 11(a) The distribution of temperature as a function of depth and time in the southwest Gulf of Mexico (22^{o}N-94^{o}W) from 8 November 1970 to 3 November 1971. Based on "V.Uribe" data.

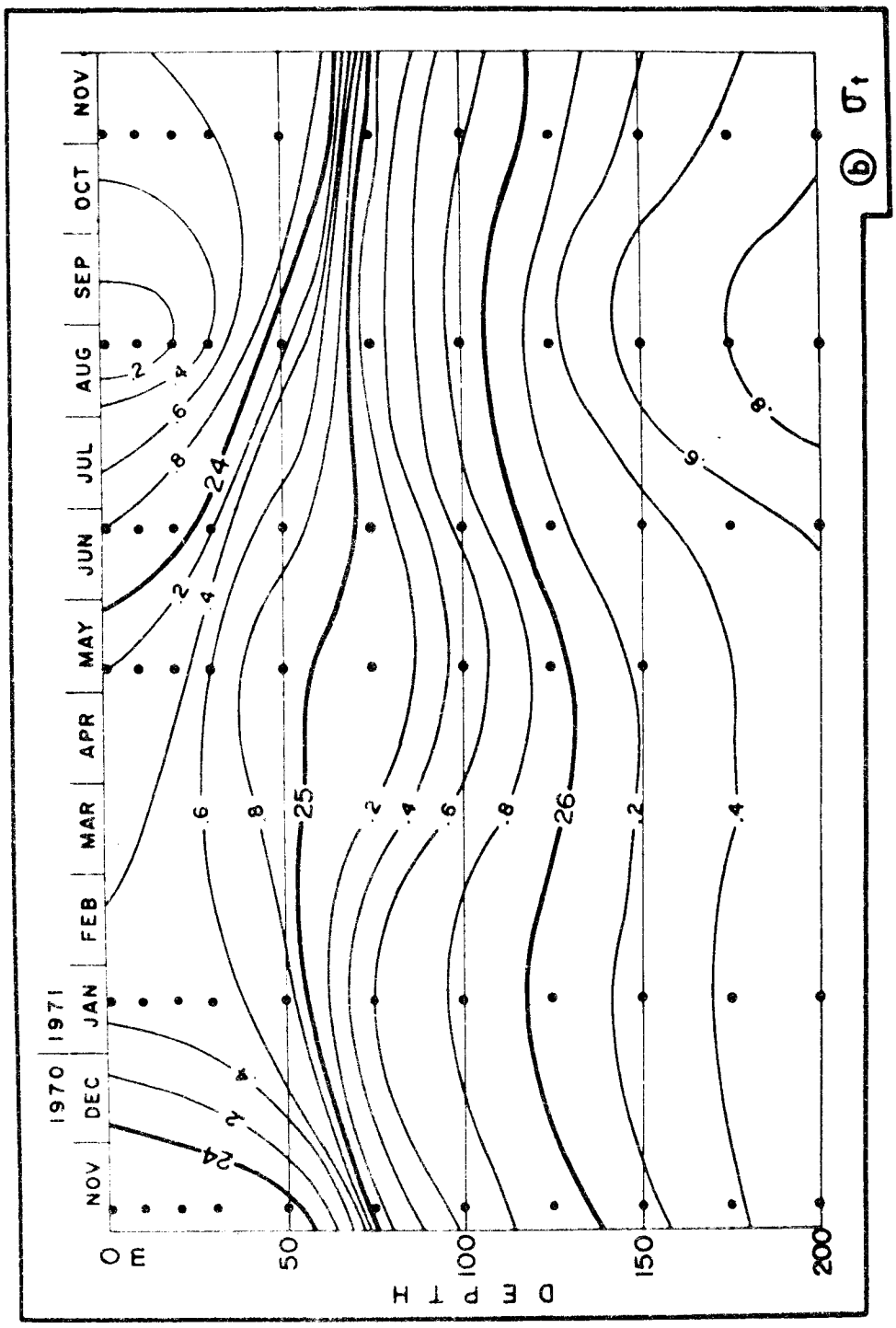


Fig. 11(b) The distribution of density as a function of depth and time in the southwest Gulf of Mexico (22^{o}N-94^{o}W) from 8 November 1970 to 3 November 1971. Based on "V.Uribe" data.

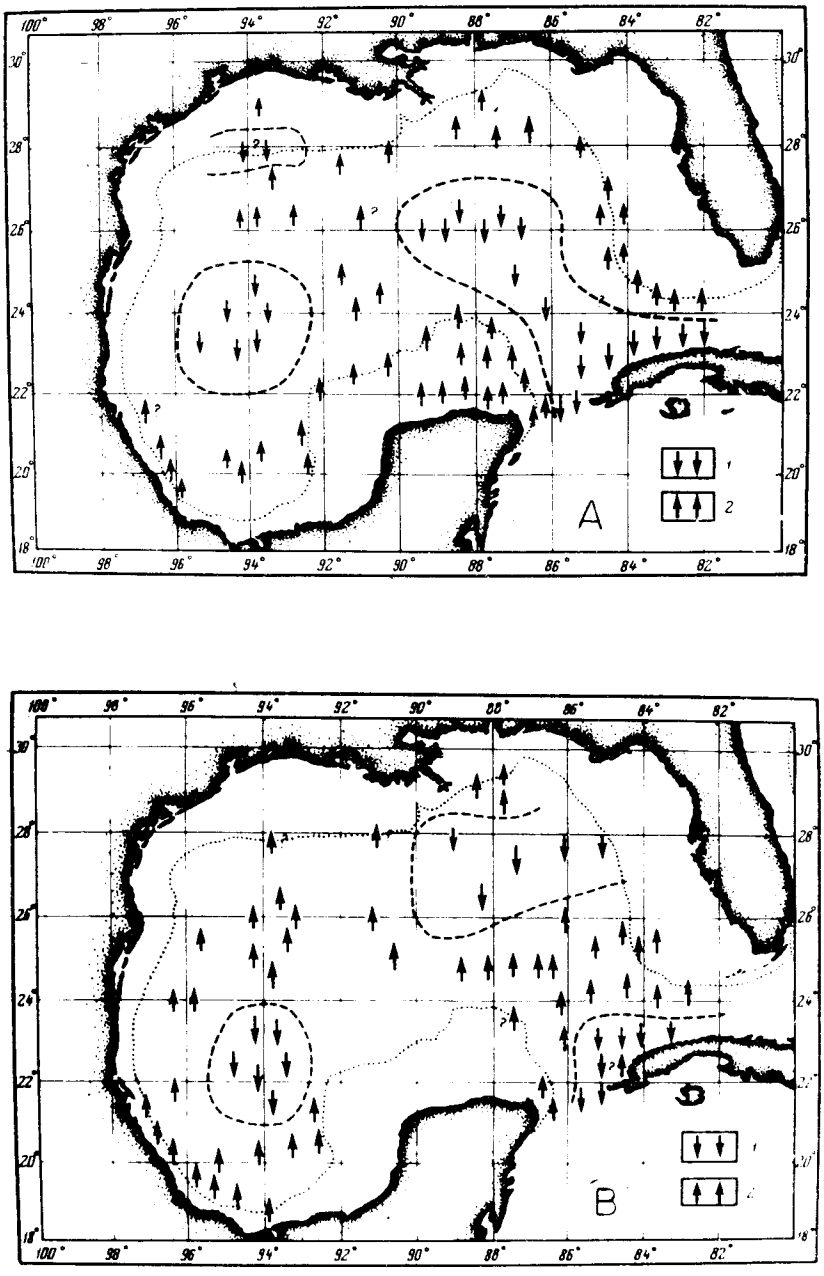


Fig. 12 Regions in the Gulf of Mexico with sinking (↓) and upwelling (↑) in the upper 200 m, during summer (A) and winter (B). (After VNIRO, 1967)

depth (some 2,000 m) are permanently stable and that no major vertical mixing or diffusion takes place. Throughout the Gulf we find a layer of maximum salinity with its core at about 36.5°/oo between 100 and 200 m. deep. This is the so-called subtropical underwater that has its origin at the surface in the subtropical regions of the North Atlantic (see, for example, Nowlin, 1972: 24).

The subtropical underwater layer in the Gulf is only intercepted along the eastern edge of the Campeche Bank where, for dynamic reasons, it reaches the surface and mixes with the top layer. Therefore, this area is the only place in the Gulf where deeper waters can be expected to move continuously upwards and bring nutrients in considerable quantities to the surface layer. Other areas, where the salinity maximum has been found occasionally to come close to the surface, are found in the southernmost part of the Campeche Bay, off the Texas Shelf and the West Florida Shelf.

Below the sill depth there is neutral stability and the fact that the basin waters in the Gulf are well ventilated, with oxygen contents slightly above 5 ml l^{-1}, as on the sill in the Yucatan Channel, shows clearly that vertical movements must take place in the basin.

On the other hand, the T-S-O relations in the deep layers of the Gulf show water masses that are practically identical to those found at similar depths in the Cayman Sea, a fact that leads to the conclusion that the water masses above the sill depth in the Gulf move only horizontally, with insignificant vertical mixing. This places the Gulf in a unique position among semi-enclosed basins in the sense that it is well stratified and yet each layer, even below the sill, exchanges water with the exterior at a considerable rate. This circumstance can only be accounted for by the configuration of the entrance and of high energy waters that are present there.

5. Water Balance and Transport in the Gulf of Mexico

5.1 Water balance

Many investigators have attempted to estimate the global water balance of the Gulf. Maul (1976) has summarized these estimates. The mean run-off from land (R) is found to be 71.5 cm per year. Single values vary from 50.5 cm per year in 1963-1965 to 105.4 cm per year in 1973. For the evaporation-less-precipitation term (E-P), Maul gives a mean of 78 cm per year. Single values vary from 35 cm per year to 121 cm per year. Thus the Gulf is estimated to be a net evaporation basin, under average conditions, with

$$R - (E - P) = -6.5 \text{ cm. per year}$$

which means that, if the average values are close to reality, it would take about 3,000 years to reduce the water level by 200 m and 23,000 years to eliminate all water from the basin. Therefore, in view of the small value and the uncertainties that still exist in its determination, we may consider the annual water balance to be zero. This is to say that, if the Gulf were closed at its entrance, the mean annual level would remain stationary, which would make the Gulf unique among semi-enclosed basins in yet another sense.

Although the water level would remain stationary, a lot of other factors would change drastically with time under such isolated conditions. First of all, surface waters over the deep Gulf would start to sink deeper and deeper as salinity increased by evaporation, and the present stratification would disappear in a relatively short time. Through drainage from land, dissolved salts and man-made contaminants would concentrate in the Gulf waters and considering that some 70% of all run-off from the United States territory and half of that from Mexico ends up in the Gulf, the increase in contaminants would be very fast indeed.

5.2 Horizontal transport

Geostrophic calculations and direct observations have so far failed to give a consistent scheme of the inflow through the Yucatan Channel and the outflow through the Florida Straits. The average value for both passages is about 30 sverdrups (10^6 m^3 sec^{-1}). Observations show that there may be a variation of at least $\pm$ 5 sverdrups (Niiler and Richardson, 1973). Simultaneous measurements in the two passages have so far given quite contradictory results, showing an imbalance of 5 or more sverdrups which by the principle of continuity cannot exist for any length of time because it would change the sea level over the Gulf by about 30 cm per day on average. Although the Gulf serves as a buffer for small differences between the inflow and the outflow, differences of this magnitude would create a pressure field to restore the equilibrium.

We have seen that the path of the Loop Current changes its features quite frequently by penetrating northward and then retreating, often hatching a large eddy in the process. Transport estimates for the Loop Current give an average of 30 sverdrups, and interestingly enough the detached eddy has also a similar transport around its centre, as shown by Merrell et al. (1976). As the eddy moves westwards it displaces the resident waters which must then leave the Gulf area. It may be estimated that a normal size eddy of 180 km in diameter, say, constitutes some 3% of the water in the upper 1,000 metres of the Gulf, so that 30 such packets would be needed to replace the entire layer.

For the western Gulf, Vazquez (1976) has calculated geostrophic transports of 10 sverdrups in the anticyclonic gyre which is about one third of what the original eddy was moving at the time of detachment. For the Campeche Bay we have, using the Mexican CICAR data, calculated the geostrophic transport of the cyclonic gyre to be near 5 sverdrups around its centre.

6. Concluding Remarks

Our knowledge of the circulation and transport in the Gulf of Mexico has advanced considerably in the last few years. More is known than before about the features of the current system in general and its variability which has proven to be so large that it becomes in many ways meaningless to talk of average climatological conditions; it would be more realistic to assess the probability parameters of transport and circulation patterns. More has been found out about the dynamics of the high energy area at the entrance of the Gulf: how the large anticyclonic eddies are hatched by the Loop Current and how they take with them mass, heat, as well as kinetic and potential energy, from the Loop Current into the western part of the Gulf.

It has also been established that communication between the different layers is very limited within the Gulf proper so that, with the exception of the upper 200 m layer, the water masses enter and leave the main part of this semi-closed basin without suffering any major transformation. Further, dynamic considerations, as well as theoretical and physical models, have helped us to understand partially how this intricate mechanism works. Yet, in spite of these advances, we have to confess that we still know very little about the quantitative aspects of many of the basic processes. We urgently need to learn more about:

i) the rate of water exchange between the Gulf and adjacent areas;

ii) the rate of exchange between the different areas within the Gulf and between the different layers;

iii) the exchanges and interaction with the atmosphere and the surrounding coastal area.

We need further to understand the role of the Gulf Stream system and its effects, direct or indirect, on the circulation in the North Atlantic.

Besides the technique of direct simultaneous measurements, we have at our disposal the remote sensing of satellites which have been proved the utmost utility in detecting, for example, small- and medium-scale features along the flanks of the main flow. More elaborate studies on the salt and water balance, as well as natural or artificially introduced trace elements, would also move us closer to full understanding. The waters from the surrounding lands carry into the Gulf large amounts of dissolved substances. Many of these elements are chemically persistent as well as recognizable. Such contaminants, since they are around anyhow, could be taken advantage of as tracers, and ultimately used for the evaluation of water exchange within the system.

The problem of contamination and renewal of the Gulf waters is another testimony of the global importance of oceanographic research, and it cannot be considered of interest only for those who live in the area or exploit the resources of the Gulf. Besides, owing to its geographical situation and adequate size, the results obtained in the Gulf can be extrapolated to other parts of the world ocean. Therefore, the investigations on the Gulf of Mexico are of universal interest.

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POLLUTION RESEARCH AND MONITORING FOR HEAVY METALS

by E. Mandelli

CONTENTS

1. Introduction

Research on trace elements has met with strongly growing interest in recent years. This is partly a consequence of a concern for the protection of the environment, and of increasing awareness of the role of trace elements and their effects on living organisms.

The identification of potentially toxic levels of trace metals in the marine environment is difficult, inasmuch as the natural levels of these materials are poorly known.

Relatively high trace metal inputs from human activities into estuarine and coastal waters have been observed, but lack of baseline data makes man-induced processes difficult to assess. Although some progress has been made in distinguishing between natural and human mobilization of trace metals, the criteria used hitherto are largely empirical and, at best, subject to doubt in many cases.

The possible short- and long-term effects caused by the introduction of trace metals into the marine environment are even more difficult to ascertain owing to our poor understanding of the factors that regulate their fate in the oceans. It is clear that a great deal of research still has to be done on the effects of enhanced concentrations of trace metals on aquatic ecosystems. Fortunately, the development of new and improved analytical methods has made it possible to study and monitor trace metals at extremely low concentrations.

2. Trace Elements in Natural Waters

Trace elements are present in natural waters in concentrations of micrograms or less per litre (Table 1). These elements have chemical properties described as metallic, non-metallic and amphoteric. The term "heavy metals" essentially implies those elements that in the metal form show specific weights above 5.

Most of the biologically active as well as potentially toxic heavy metals are members of the family of elements known as the transition series in the periodic table (Table 2). Transition metals have many properties in common, because of their similar valence electron configuration; they are highly reactive and are therefore accumulated in authigenic minerals and organisms in the aquatic environment.

Most of the potentially toxic trace elements listed in Table 1 are transition metals from the first series. However, some of them, such as copper and zinc, are uniquely qualified as effective catalysts in biological systems at very low concentrations. Other transition elements, such as silver, cadmium and mercury, are foreign to metabolic functions in organisms, and a hazard to human health. Another metal of great concern is lead, because additions by man to the marine habitat exceed those mobilized naturally. The impact of these lead additions is unknown, but could affect organisms both somatically and genetically.

With regard to the non-metallic and amphoteric elements, our attention has been focussed particularly on arsenic and selenium. These elements can

Table 1

Concentration of potentially toxic trace elements in natural waters (1)

Element	Concentration ($\mu g\ l^{-1}$)	
	Oceans	Rivers
Silver (Ag)	0.28	0.3
Arsenic (As)	2.6	2
Cadmium (Cd)	0.11	N.D.(2)
Chromium (Cr)	0.2	1
Copper (Cu)	2	7
Mercury (Hg)	0.15	0.07
Nickel (Ni)	2	0.3
Lead (Pb)	0.03	3
Vanadium (V)	1.9	0.9
Zinc (Zn)	2	20

Notes: (1) From Skinner and Turekian (1973).

(2) N.D. : No data or reasonable estimates available.

Table 2

Partial reproduction of the long-term period form of the periodic system

IIIa	IVa	Va	VIa	VIIa	VIII			Ib	IIb	IIIb	IVb	Vb	VIb
Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34
Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52
*	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84

Notes: ▢ Metals of environmental concern.

* Lanthanides.

be mobilized within the aquatic environment by micro-organisms, thus forming organo-non-metallic compounds which may be of ecological significance (Jernelov and Martin, 1975).

The state of trace elements in natural waters has been the focus of interest of chemical as well as biological studies (Stumm and Bilinski, 1973). It is usually very difficult to establish the prevalent metal species present in natural waters. Data on the formation of labile and non-labile complexes between trace metals and the major inorganic components in aquatic systems was reported by Gardiner (1974), Chau and Lum Shue Chan (1973). On the chelation of trace elements by naturally occurring organic matter, no soluble chelates have been detected by any direct method, nor have they been isolated from natural waters (Bertine and Goldberg, 1971).

Metal-complex formation in the aquatic environment could have important consequences, both regarding toxicity to aquatic organisms, and the extent of their disappearance from solution by precipitation and adsorption.

3. Transfer Pathways

In the absence of human activities, weathering and vulcanism are the principal pathways that trace elements follow from the continents to the oceans. Cultural sources of trace elements introduced into the marine environment are land erosion, caused by its intensive use, and the disposal of wastes.

In Table 3 are shown the fluxes of materials mobilised by nature and by man to the oceans. The mass of continental material moved to the oceans by rivers, winds and glaciers is estimated to have increased from 9.3×10^9 tons per year to 24×10^9 tons per year (Judson, 1968), and the quantities of the trace elements have probably increased at least proportionately. It is also important to point out that the amount of wastes produced by man is about one-tenth of that involved in the already modified weathering process.

3.1 Streams

The role of rivers in transporting materials from the continents to the oceans seems paramount, being about ten times greater than that of glaciers, and about one hundred times greater than that of the winds (Goldberg, 1976).

The sediment load of rivers is difficult to estimate; however, a world average of 400 mg l^{-1} was estimated by Turekian (1971). The average world-wide dissolved load, on the other hand, is thought to be about 120 mg l^{-1} based on the compilations of Livingston (1963). A summary of selected data is presented in Table 4.

The trace element composition of streams is more difficult to ascertain. Not only is it probable that there are regional variations due to the type of rocks being weathered, and the degree of weathering, but also by the no longer trivial cultural input. Gibbs (1973) identified five mechanisms of trace-

Table 3

Natural and man-induced flux of materials
to the marine environment (1)

Materials	Sources	Flux (10^9 tons per year)
Particulates + Dissolved	Rivers	21.9
Particulates	Glaciers	3.0
Wastes (2)	Outfalls + ships	3.1
Particulates + Aerosols	Atmospheric precipitation	?

Notes: (1) From Goldberg (1972)

(2) Estimate from total wastes produced by man.

Table 4

Average suspended and dissolved loads of streams in various regions of the United States compared with the Amazon river

Region	Drainage ($x10^3 km^2$)	Runoff ($x10^{15}$ l. per year)	Average	
			Suspended Load (mg l^{-1})	Dissolved Load (mg l^{-1})
U.S. rivers (1)	6,807	1,485	602	214
Amazon (2)	6,300	5,500	100	36

Notes: (1) From Judson and Ritter (1964).

(2) From Gibbs (1967).

metal transport in rivers: (i) in solution; (ii) adsorbed in inorganic solids; (iii) as metallic coatings on solids; (iv) in organic solids; and (v) in detrital crystalline material. In a study designed to determine the amounts of trace metals transported in the Amazon and Yukon rivers by each of these mechanisms, Gibbs found similar results for all the trace metals analyzed. This similarity is particularly significant since the two rivers are in extremely different climates and are both largely unpolluted (Table 5).

Although it is useful to know the average trace metal composition of streams, it is also necessary to have some idea of the degree of variation down the length of the stream. This will show the effect of reactions within the streams and the effect of man-induced sources.

3.2 Aerial transport

Atmospheric transport of trace elements from the continents to the oceans and vice-versa is effected by aerosols, particles of sufficiently small size to remain airborne for long periods of time.

The global dissemination of atmospherically introduced substances can be initially considered through the main air-mass movements, the equatorial easterlies, the temperate westerlies, and the polar easterlies. Superimposed on such patterns are the smaller-scale winds, often arising from the differing effects of continental and oceanic masses upon air movements, such as the monsoons.

There are two natural sources of very fine, atmospheric particulates, sea salts and continental dust. The main portion of the tropospheric aerosol mass is represented by particles ranging in radius from 0.1 μm to 20 μm (Clough, 1973).

Another source of trace elements on atmospheric particles are high-temperature processes, either natural (vulcanism) or induced by man. In both cases the more volatile elements are emitted either in the gas phase or on very small particles. Two major contributing sources are the combustion of fossil fuels and the production of cement. Estimates of the mobilization of elements from fossil-fuel burning and cement production have been made by Bertine and Goldberg (1971), and are shown in Table 6.

The transfer of particles from the atmosphere to the oceans takes place by gravitational settling (dry fallout) or by means of washout caused by rain, snow or sleet. In Table 7 the concentrations of trace elements in air and in rainwater are shown (Peirson *et al.*, 1973).

With regard to the distribution of trace elements in the atmosphere, Bruland *et al.* (1974a) observed similar concentrations in atmospheric samples from the British Isles and California. Moreover, recent work on Antarctic atmospheric dust samples reveals a close correspondence in their heavy metal concentrations with those of the British Isles and California. This seems to indicate the possibility of a world-wide dust burden in the atmosphere (Goldberg, 1976).

Table 5

Percentages of the total amounts of iron, nickel, cobalt, chromium, copper and manganese transported by the Amazon river (1)

Mechanism	Element					
	Fe	Ni	Co	Cr	Cu	Mn
In solution	0.7	2.7	1.6	10.4	6.9	17.3
Adsorbed	0.02	2.7	8.0	3.5	4.9	0.7
Precipitated	47.2	44.1	27.3	2.9	8.1	50.0
In organic solids	6.5	12.7	19.3	7.6	5.8	4.7
In crystalline sediments	45.5	37.7	43.9	75.6	74.3	27.2

(1) From Gibbs (1973)

Table 6

Amounts of heavy metals mobilized into the atmosphere as a consequence of human activities compared to those resulting from weathering (1)

Element	Mobilization (10^9 g per year)			
	Fossil-fuel	Cement	Weathering	
			River flow	Sediments
Silver (Ag)	0.07	-	11	0.03
Arsenic (As)	0.7	3.2	72	-
Cadmium (Cd)	-	0.08	-	0.5
Chromium (Cr)	1.5	-	36	200
Copper (Cu)	2.1	-	250	80
Mercury (Hg)	1.6	0.1	2.5	1
Nickel (Ni)	3.7	-	11	160
Lead (Pb)	3.6	30	110	21
Vanadium (V)	12	-	32	280
Zinc (Zn)	7	32	720	80

(1) From Bertine and Goldberg (1971)

Table 7

Trace element concentrations in air and rain from Wraymires, England (1)

Element	Concentration		
	In air (ng kg^{-1})	In rain (µg l^{-1})	CF
Arsenic (As)	2.5	1.6	640
Cadmium (Cd)	3.0	17.7	6000
Chromium (Cr)	10.6	8.1	810
Copper (cu)	26.0	23.0	880
Mercury (Hg)	0.17	0.2	1000
Lead (Pb)	87.0	39.0	450
Selenium (Se)	0.9	0.34	380
Zinc (Zn)	80.0	85.00	1050

(1) From Peirson et al., (1973).

3.3 Coastal outfalls

The possible short- and long-term effects of the disposal of trace metals in the coastal environment through outfall systems are a matter of great concern. Rational management of such disposals is made difficult by lack of understanding of the factors that regulate the fate of trace metals in the oceans (Huntzicker et al., 1975).

One of the better documented studies on heavy metals in domestic and industrial sewage is that carried out by the Los Angeles County Sanitation District in the Joint Water Pollution Control Project (JWPCP).

The JWPCP outfall system is well suited for a study of the contribution of metallic pollutants by waste water to the coastal environment.

The quantities of waste water from this sewage system are very large: 540×10^9 l per year for 1971 compared to the Colorado river runoff contribution, which is about $21{,}000 \times 10^9$ l per year. The waste water consists of both domestic and industrial sewage containing relatively high metal concentrations. Table 8 gives the average concentration of eleven trace metals in the treated effluent (Morel et al., 1975).

This sewage treatment system is typical of commonly-used primary treatment. The sludge is digested anaerobically, centrifuged and remixed with the primary effluent, contributing much of its particulate and metal loads. The waste water is discharged through two main submarine outfalls, both discharging at a depth of 60 metres at the edge of the continental shelf.

For several metals, such as iron, zinc, chromium, copper, lead, nickel, cadmium and silver, the contribution of the JWPCP outfall system to the coastal area accounts for more than a quarter of the total input, estimated as the sum of sewers, rivers, dry fallout, dumping and other discrete sources.

3.4 Dumping

Disposal of wastes deliberately and unintentionally in coastal waters is responsible for the dispersion of pollutants locally and globally. Most dumping of wastes and continental materials occurs over the continental shelf, and the wastes are mainly composed of dredge spoils, sewage sludges, fly ash and a variety of liquid and solid wastes from chemical processes.

Knowledge of the amount, composition or distribution of waste materials in coastal waters around cities is limited. The disposal activities have been carried on for generations with little or no regulation or record.

The largest operation of intentional dumping takes place in the coastal area near New York City. According to Gross (1970 a) about 8.6 million tons of material were disposed of every year between 1964 and 1968.

Table 8

Trace metals in the waste waters of the Los Angeles County Sanitation District sewage outfall system (1)

Element	Concentration ($\mu g\ l^{-1}$)			Mass Emission Tons per year
	Waste water	Sea water	Ratio	
Silver (Ag)	20	0.3	70	11
Cadmium (Cd)	30	0.1	300	16
Cobalt (Co)	10	0.2	50	5
Chromium (Cr)	860	0.2	4,000	460
Copper (Cu)	560	3.0	200	300
Iron (Fe)	9,900	10.0	1,000	5,300
Mercury (Hg)	1	0.03	30	0.5
Manganese (Mn)	130	2	70	70
Nickel (Ni)	240	6	40	130
Lead (Pb)	250	0.04	6,000	140
Zinc (Zn)	2,400	10	250	1,300

(1) From Morel et. al. (1975).

Dredge spoils accounted for 80 per cent of the total, with domestic and industrial wastes amounting to 10 per cent each.

Recent reports on the levels of ocean dumping in the USA indicate a volume of nearly 88 million cubic yards of dredge materials, 5 million tons of municipal waste and 3.5 million tons of industrial wastes (USDC, 1976).

Waste dumped in coastal areas consists of at least three components: organic matter, including sewage solids; silicate materials; and small quantities of industrial wastes. Gross (1970 b, c) showed that several heavy metals are present in the wastes at concentrations in excess of those observed in sediments unaffected by waste disposal activities. Additional investigations of the chemical nature of the dumped dredge spoil in the New York Bight revealed levels of heavy metals as high as those of sewage sludge (Pearce, 1972).

The concentration of trace metals in particulates from domestic and industrial waste waters was reported by Bruland et. al. (1974a). In Table 9 the concentrations of heavy metals in waste water particulates from three outfall systems inthe Los Angeles area are shown.

4. Fates

Heavy metals introduced into the marine environment from whatever sources go through a variety of transformations involving physical, chemical, and biological processes. These processes begin to operate during transport by air or by water.

Once heavy metals have reached the marine environment, an understanding of their distribution, dispersion and transformation in the water column and the various interfaces is critical. This section attempts to identify the major factors controlling the fate of heavy metals in the marine environment through the formation of complexes, bio-accumulation, biological transformation, sedimentation, etc.

4.1 Chemical speciation

The state of trace metals in the aquatic environment has been the focus of interest of chemical, as well as biological, studies. It is well known that a complexation of metals by the various inorganic ligands and the organic compounds in natural waters maintains a reservoir of metals in solution . In Table 10 the different forms of occurrence of metal species in natural waters are shown (Stumm and Bilinski, 1973).

Although thermodynamic models have been devised to describe the distribution of metals among the various dissolved complexes, there is insufficient knowledge of the equilibrium constants between the metals and the different ligands, as well as a lack of information on the activities of the reacting species (Goldberg, 1976).

While date on the stability of hydroxo- complexes has become available, information on trace-metal complexes with other ions of the medium is still lacking. In addition to inorganic complexes, there are

Table 9

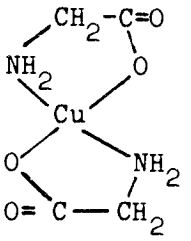
Heavy metals in waste water particulates from three outfall systems of the Los Angeles County Sanitation District (1)

Element	Concentration (mg kg^{-1})		
	Whites Point	Hyperion	Orange County
Silver (Ag)	32	130	40
Cadmium (Cd)	65	108	245
Cobalt (Co)	8	4	6
Chromium (Cr)	1,700	1,440	1,330
Copper (Cu)	1,120	1,500	1,850
Iron (Fe)	20,000	5,400	7,000
Manganese (Mn)	150	108	120
Nickel (Ni)	220	520	220
Lead (Pb)	570	320	920
Zinc (Zn)	4,100	2,300	2,300

(1) From Bruland et al. (1974a).

Table 10

Forms of occurrence of metal species in natural waters (1)

Free metal ions	Inorganic ion pairs and inorganic complexes	Organic complexes and chelates	Metal species complex bound to high-molecular weight-organic material	Metal species in the form of colloids and sorbed on colloidal materials
$Cu.aq^{2+}$	$Cu_2(OH)_2^{2+}$	Me-SR (2)	Me-lipids (2)	FeOOH
$Fe.aq^{3+}$	$Pb(CO_3)_2^{2+}$	Me-OOCR (2)(3)	Me-humic acid (2) polymers	$Fe(OH)_3$
$Pb.aq^{3+}$	$CuCO_3$			Mn(IV) oxides
	AgSH			$MeCO_3$, MeS, etc.(2)
	$CdCl^+$		Me-polysaccharides (2)	on clays, FeOOH
	$CoOH^+$			on Mn oxides
	$Zn(OH)_3^-$			
Diameter range :	——— 10 Å ———		100 Å ———	1000 Å

Notes: (1) Stumm and Bilinski, 1973.

(2) Me - Metal

(3) R - Organic radical

miscellaneous organic compounds in natural waters which can form complexes with metal ions as well as form organo-metallic compounds of the metal-carbon bonding type. Stumm and Morgan (1970) studied the possible chelating influence of organic compounds in aquatic systems, concluding that free metal aquo- ions, or their hydroxo- and carbonato- complexes are the predominant species even if complex-forming organic matter is present.

New analytical methods have now become available to elucidate the type of metal-ion species encountered in waters, and to determine solubilities in the 10^{-6} to 10^{-7} concentration range. Anodic stripping voltametry, square wave and pulse polarography are convenient methods of identifying the various species and in distinguishing physical and chemical forms (Piro et al., 1973; Chau, 1973).

ASV does not merely measure total metal concentration, but detects some fraction of the metal soluble species, the free (hydrated) ions, inorganic complexes such as chloro-, hydroxo- and carbonato- species, and various organic complexes. However, particular caution must be exercised for the organic-rich waters because of sorption effects over the hanging mercury drop (Brezonik et al., 1976).

4.2 Physico-chemical processes

As with other pollutants, the transfer of heavy metals in the oceans depends on the physical distribution between dissolved and particulate phases, and on their chemical behaviour. Processes, such as adsorption, precipitation, colloidal flocculation or biological uptake, act by scavenging heavy metals from the water column and accumulating them in the sediments. In this respect Turekian (1971) indicated that despite the injection of trace metals by streams (whether natural or artificial) very little of the metals leave estuarine areas in dissolved form.

Trace metals, after desorption from inorganic phases, are incorporated into organic materials that accumulate in the sediments or in the surface microlayer. Through decay in the sediments most of the heavy metals are further immobilized as sulphides or reduced oxides.

Although heavy metals enter estuaries from many natural sources (De Groot, 1973), one of the most important sources is undoubtedly ordinary municipal waste water. Before discussing the behaviour of sewage upon dilution in the receiving waters, it is first necessary to understand the redox level and speciation of the metals in sewage. Table 11 shows a chemical equilibrium model of the trace-metal species in sewage from the JWPCP outfall system of Los Angeles, USA, based on experimentally determined parameters. Most of the trace metals in the JWPCP sewage are in the suspended matter as insoluble sulphide or oxide forms. The very reduced and metal-rich nature of this sewage is not typical of all sewage discharges from marine outfalls (Morel et al., 1975).

As sewage enters the coastal environment, it is simultaneously diluted and oxidized. The significant effect of oxidation on most metals is the dissolution of sulphides. This solubilization increases the metals' retention time in the water column, and ensures a very high dilution,

Table 11

Chemical equilibrium model for trace metals in sewage from the Los Angeles Sanitation District (1)

Element	Total Concentration -Log	Inorganic Model	%
Silver (Ag)	6.7	Ag_2S (s)	100
Cadmium (Cd)	6.5	Cd S (s)	100
Cobalt (Co)	6.8	Co S (s)	97
		Co^{2+}	2
Chromium (Cr)	4.8	$Cr(OH)_3$ (s)	97
		$Cr(OH)4^-$	3
Copper (Cu)	5.0	Cu S (s)	100
Iron (Fe)	3.7	Fe_3O4 (s)	100
Mercury (Hg)	8.3	Hg S (s)	100
Manganese (Mn)	5.6	Mn^{2+}	50
		$Mn\ HCO_3^+$	24
		$Mn\ SO_4$	19
		$Mn\ Cl^+$	6
Nickel (Ni)	5.4	Ni S (s)	42
		Ni^{2+}	2
		$Ni\ (CN)_4^{2-}$	
Lead (Pb)	6.0	Pb S (s)	100
Zinc (Zn)	4.5	Zn S (s)	100

(1) From Morel et al. (1975)

according to the model. Hence the farfield concentration of metals should not be increased measurably over the natural background levels. In the nearfield area of the outfall, on the other hand, the settling of solid species and the bacterial activity maintaining the redox levels of the effluents are expected. Under these conditions only nickel, manganese and possibly cobalt are likely to be dissolved from the sediments.

The fate of copper, zinc, cadmium and lead in an estuarine environment, Chesapeake Bay, upon the release of waste water was studied by Helz et al. (1975). The authors attribute the disappearance of the metals from solution not to dilution, but to rapid immobilization mechanisms, not clearly identified. The sediment has suggested that the metals removed from the water column are transported along the bottom, and that cadmium and possibly manganese re-enter the water column in the mixing area near the mouth of the estuary (Figure 1).

As mentioned previously, it appears that particulate trace metals may be accumulated, not only in the sediments, but also in the sea-surface micro-layer. Results to date suggest that in most open-ocean areas, the upward flux of many heavy metals associated with bubbles is at least of the same order of magnitude or higher than the downward flux of the same metals from the atmosphere to the sea surface (Duce et al., 1972).

4.3 Bio-transformations

Some biological processes in the aquatic environment may serve as efficient mechanisms for mobilizing heavy metals that would otherwise be lost in the sediments. Metabolic activity of micro-organisms plays a significant part in the mobility of toxic elements in the environment.

When confronted with a toxic substance, micro-organisms frequently adapt to detoxify it. By means of oxidative or reductive reactions catalyzed by enzymes, micro-organisms can convert metal species into mixtures of compounds that are in equilibrium with respect to the formal oxidation states of the metals. The biological conversion of Hg^{2+} to Hg^{o} can be regarded as a detoxification mechanism because the Hg^{o} has sufficient vapour pressure to be lost from the water into the vapour phase. Other micro-organisms can detoxify their environment of toxic metals by methylation, such as the bio-conversion of Hg^{2+} into methylmercury and CH_3Hg^{+} to dimethylmercury (Landner, 1972). Dimethylmercury is volatile, and once in the atmosphere, it is photolized by ultra-violet light to yield Hg^{o} plus methane and ethane. The poisonous neurotoxin, methylmercury, can also be biologically converted to Hg^{o} plus methane (Furukawa et al., 1969). The biological cycle for mercury is outlined in Figure 2.

By examining the periodic table and utilizing current knowledge of the properties of toxic elements, it is possible to predict how most of these elements will behave in the environment. According to Wood (1974), tin, palladium, platinum, gold and thallium can be bio-transformed in the same way as mercury in the environment, though elements such as lead, cadmium and zinc will not be methylated. This is because the lead, cadmium and zinc alkyls are not stable in aqueous solutions (Wong et al., 1975; Schmidt and Huber, 1976).

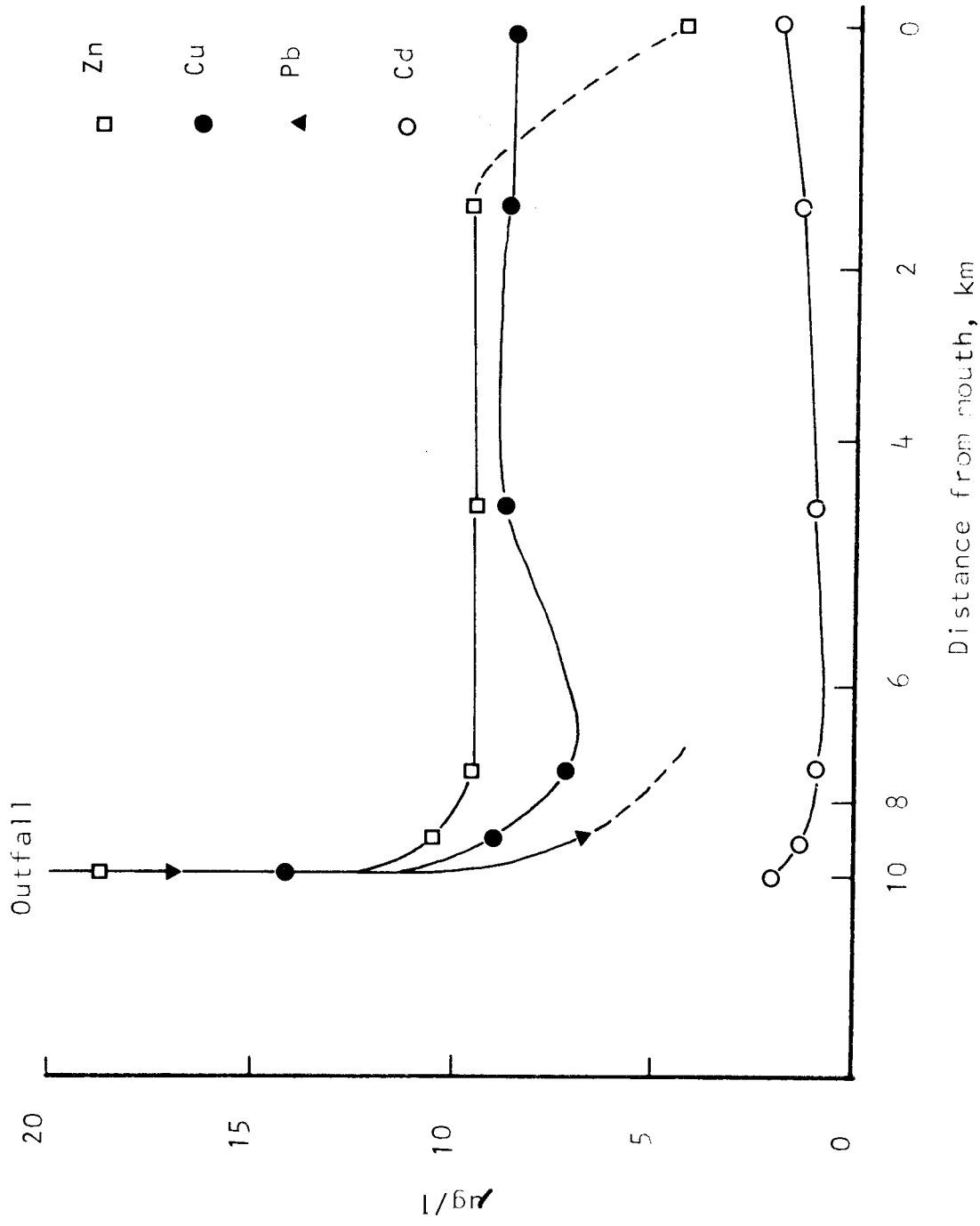


Fig. 1 Trace element concentrations after waste water discharge (Helz et al., 1975).

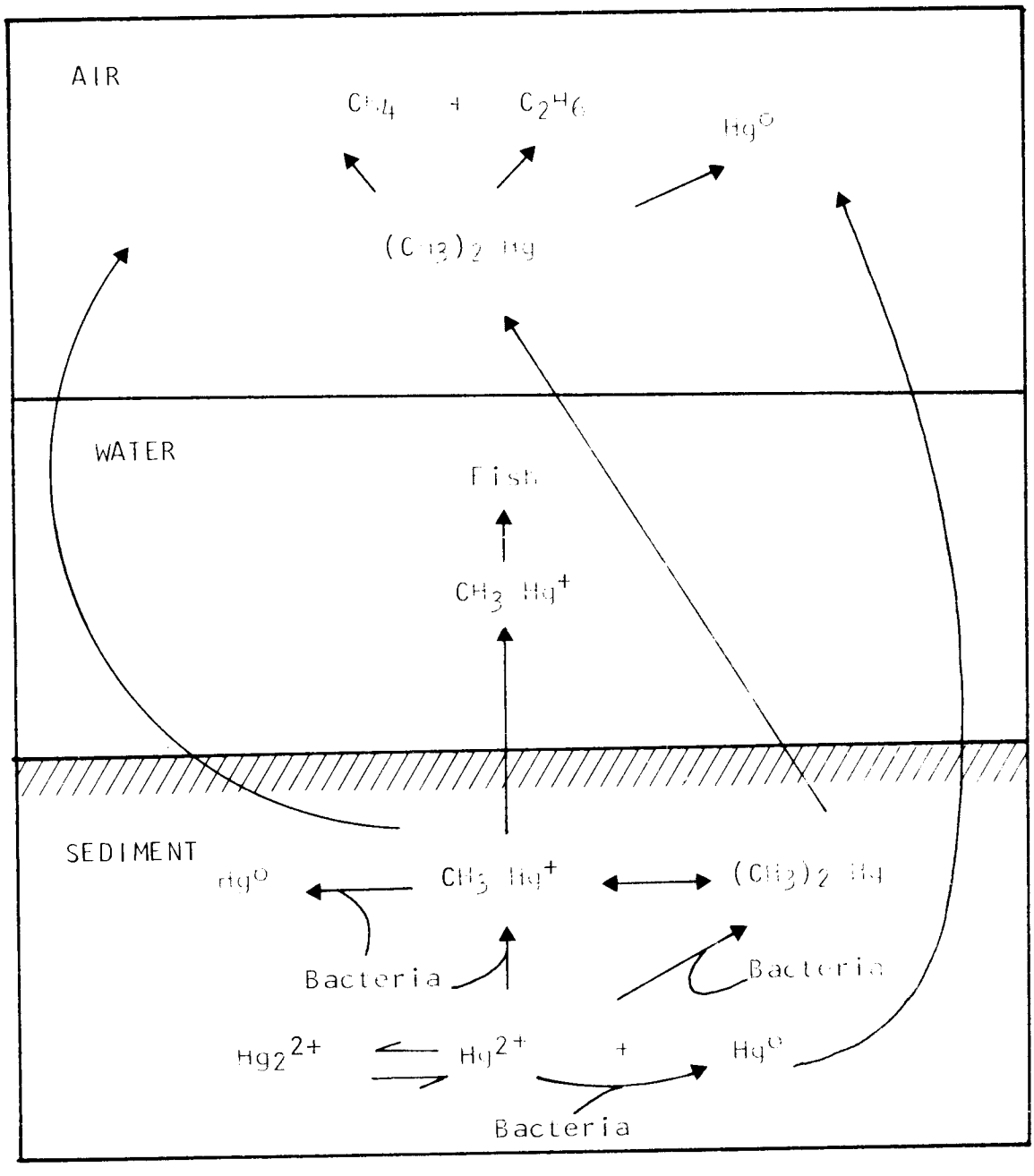


Fig. 2 The biological cycle for mercury (Wood, 1974).

Arsenic compounds are reduced and methylated by micro-organisms in the aquatic environment. Braman and Foreback (1973) reported that dimethylarsinic acid is the major form of arsenic in the environment. Dimethylarsinic acid under anaerobic conditions can be bio-transformed into dimethylarsine and trimethylarsine, both of which are volatile and extremely toxic compounds. Fortunately, these arsines are readily oxidized by oxygen to yield the less toxic dimethylarsinic acid.

On the basis of our understanding of arsenic chemistry, it is possible to predict similar bio-transformations for selenium, tellurium and sulphur. Methylation of selenium by micro-organisms contained in lake sediments was recently reported by Chau et al. (1976). Lunde (1972) demonstrated that algal cultures and fish are able to synthesize fat-soluble and water-soluble arseno-organic compounds from inorganic arsenic.

Another mechanism, currently under study, is the bio-transformation and mobilization of heavy metals in the estuarine environment by marsh and sea "grasses" (Dunstan and Windom, 1974). Spartina alterniflora takes up mercury very efficiently through its roots. This uptake is followed by transfer of mercury, as CH_3Hg^+, to the leaves where it is subsequently released into the water column. Preliminary results also suggest that an oxidized micro-layer exists around the roots that facilitates the incorporation of metals into the seagrass from the sediments.

4.4 Bio-accumulation

Bio-accumulation is the phenomenon that, through whatever reason or mechanism, results in an organism or a particular tissue of that organism accumulating a higher concentration of chemical species than that which is present in their environment. Since levels of most contaminants in the aquatic environment are low and their determination poses great difficulties, the accumulation capacity of certain organisms has led to their adoption in monitoring programmes.

Several mechanisms have been proposed for the uptake and loss of trace elements in aquatic organisms, particularly heavy metals. Romeril (1971) summarized the following uptake pathways:

(i) Adsorption of ions at membrane-water interfaces;

(ii) Adsorption of active and/or passive diffusion of metal ions from seawater across semi-permeable membranes into the body fluids;

(iii) Ingestion of ions with food or in combination with particulate matter and adsorption through the gut wall.

Bryan (1971) proposed two mechanisms for the loss of heavy metals from marine organisms:

(i) Excretion across the body surface or gills;

(ii) Excretion via the gut and the urine.

Living organisms have a dynamic relationship to their environment; therefore, it is frequently observed that trace elements are both accumulated and excreted until a steady state has been attained. Schulz-Baldes (1974) reported on the uptake and loss of lead by the mussel, Mytilus edulis, for short periods of time under laboratory conditions. The results of these experiments indicated that the rate of uptake is proportional to the concentration of lead in the medium, and the rate of loss proportional to the concentration of lead in the tissues. Consequently, at a constant load concentration in the medium the rate of uptake is constant while the rate of loss increases with higher concentration in the tissues.

In the loss of mercury and copper from the oyster, Crassostrea virginica, Cunningham and Trip (1973) and Mandelli (1975) observed that the concentration of these heavy metals declined during a brief period; thereafter, residual levels remained constant, indicating their permanent fixation (Figure 3). Mechanisms for the regulation of metal body burdens can maintain constant metal levels in the tissues (Cross et al., 1973).

Direct relationships with the environment, as well as physiological stresses, can also result in reduced levels of accumulation and loss. In Table 12 the effects of some of these factors on the accumulation of copper by Crassostrea virginica are shown.

It is necessary to point out that an important part of the uptake of heavy metals by marine organisms takes place through suspended particulates and food where the metals are preconcentrated (Ayling, 1974; Hardisty et al., 1974; Patrick and Loutit, 1975). Thus accumulation factors describing the ability of certain organisms to concentrate heavy metals from seawater appear meaningless where there are high concentrations of metals in organic and inorganic particulates.

Another noteworthy characteristic of the bio-accumulation process is the specificity of certain organisms in accumulating a given metal; e.g., the accumulation of vanadium and niobium by tunicates. Goldberg (1976) considers this specificity to be due to macro-molecules present in the organism which provide the appropriate geometry and chemical linkage for the uptake of a particular metal from seawater.

5. Effects

Some of the concepts expressed in the section on bio-accumulation of heavy metals by aquatic organisms will be expanded here.

A considerable amount of information on the acute effects of heavy metals on commercially important aquatic organisms has been gathered through bio-assay tests (Eisler, 1973). The organisms under study are adults and frequently at high trophic levels, whereas organisms at low trophic levels, larvae and juveniles, often more sensitive, have been less investigated (Connor, 1971; Calabrese et al., 1977).

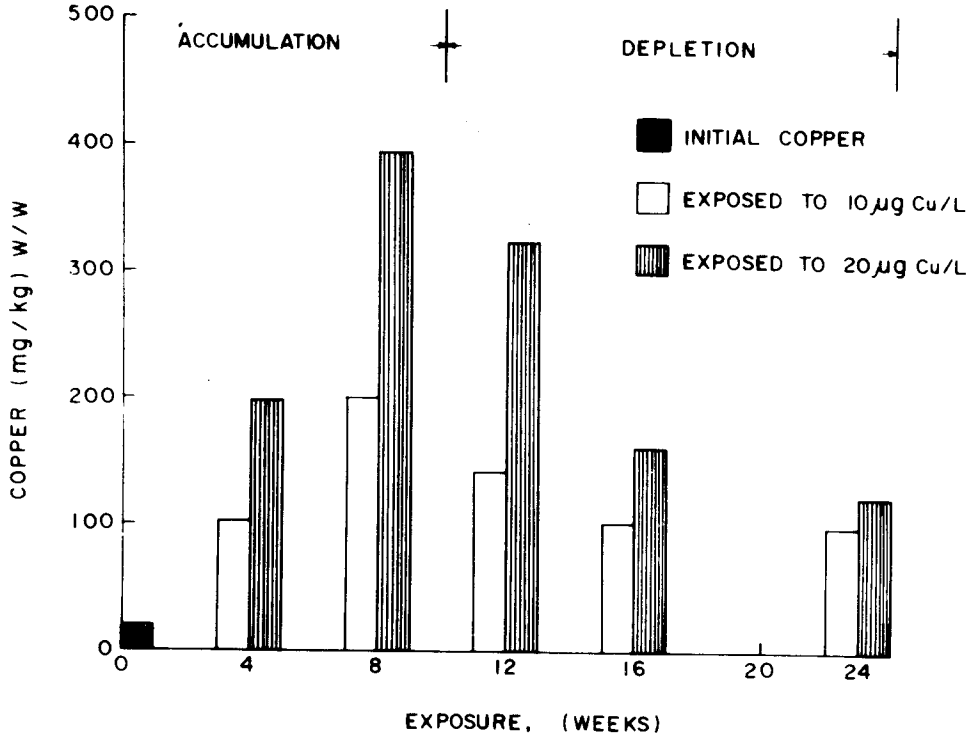


Fig. 3 Copper accumulation and loss by Crassostrea virginica (Mandelli, 1975).

Table 12

Long-term seasonal bio-assays (56-66 days) on the net copper uptake and copper accumulation rates for Crassostrea virginica exposed to seawater desalination brine mixtures (Mandelli, 1975)

Season Texas Gulf Coast	Total Copper ($g\ l^{-1}$) Seawater + brine	Exposure (days)	Accumulation $\mu g\ Cu\ g^{-1}$ (WW)	Accumulation Rate µg Cu per day
Spring	22.8	32	54.1	1.69
		34	55.0	1.61
	41.7	32	134.6	4.20
		34	105.8	3.11
Summer	19.2	29	74.0	2.55
		28	44.9	1.59
	41.7	29	189.3	6.53
		28	99.8	3.56
Fall	23.0	28	90.3	3.22
		28	83.3	3.00
	43.0	28	180.1	6.43
		28	189.0	6.75
Winter	22.0	30	98.0	3.26
		32	106.7	3.34
	39.7	30	222.0	6.94
		32	222.4	6.76

As far as protection of aquatic organisms is concerned, there is a need to know more about the effects of heavy metals on the most sensitive species, as well as on the early developmental stages. The effects of heavy metals on the viability of aquatic ecosystems also merits close examination.

Heavy metals may be a real problem in the pollution of the marine environment. Starting with the tragedies of Minamata and Niigata in Japan, we have become aware of the hazard to human health related to toxic heavy metals accumulated in seafood.

Preliminary attempts to develop regulations based on known effects of heavy metals on the aquatic biota, show that our knowledge in this area is very limited.

5.1 Aquatic organisms

In Figure 4 are shown the possible effects of pollutants upon aquatic biota.

In the particular case of heavy metals, because of their ability to form complexes with organic substances, there is a tendency for them to be fixed in the tissues of the organisms. This is perhaps one of the major problems that heavy metals pose as pollutants in the aquatic environment. While there is a moderate amount of information on the acute toxicity of heavy metals on aquatic organisms, little attention has been paid to the sublethal effects.

The problem that often exists is to try to quantify the physiological changes that occur in an organism under the stress of exposure to heavy metals. These physiological alterations include neurophysiological effects (Lindhal and Schwanbom, 1971), alterations on the enzymatic activity (Jackim et al., 1970), endocrinology, parasitology and diseases, reproduction (McIntyre, 1973), the teratogenic, carcinogenic and mutagenic effects, as well as other disorders at the cellular level.

The effects of interacting environmental variables, such as temperature, salinity and dissolved oxygen superimposed on heavy-metal stress on aquatic organisms are rarely investigated (Vernberg et al., 1974; Mandelli, 1975). Moreover, it is also essential to consider that mixtures of heavy metals can have synergistic or antagonistic effects in their toxicity to organisms (Gray, 1974). Recently it has been suggested that selenium may have an antagonistic effect on the toxicity of mercury which renders both elements less toxic to marine organisms (Jernelov, 1974). It is also well known that zinc and cadmium are bio-chemically antagonistic elements (Shakman, 1974).

Another interesting aspect of relatively high concentrations of heavy metals in the aquatic environment is the development of metal tolerance by certain organisms, as has been demonstrated by Bryan and Hummerstone (1973).

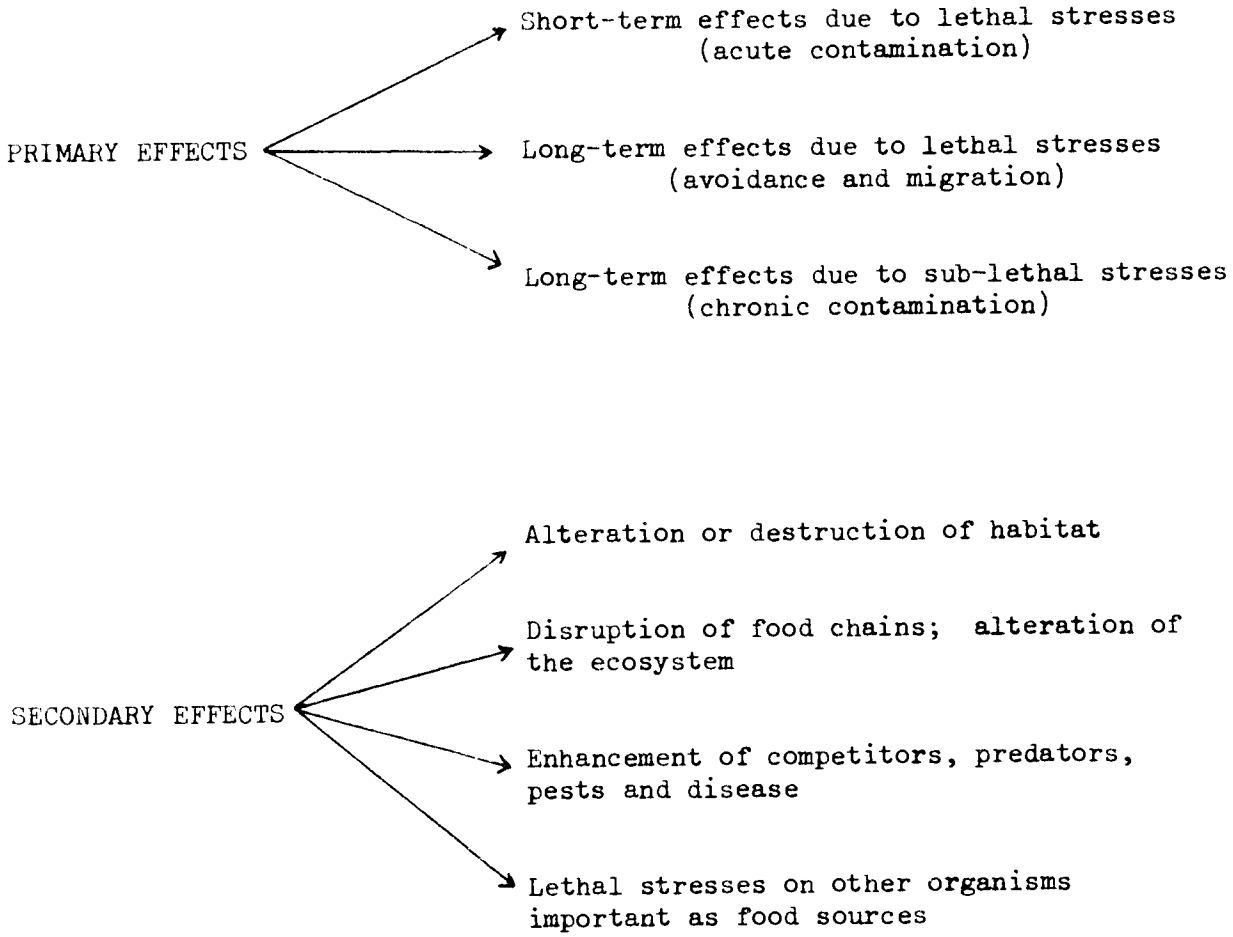


Fig. 4 Possible effects of contaminants on marine biota.

5.2 Fisheries

The economic repercussion of pollutants on fisheries is being felt in many ways; through the loss of resources, reduced fishing and difficulties in the marketing of products. The present overall economic losses from reduced fish catches, decrease in the quality of the fishery products, or hindrance to fishery activities, are difficult to estimate.

The main impact of heavy metals on commercial fisheries has been related to the difficulties in marketing the products under strict regulations. Alarm about mercury poisoning in Japan has been more responsible than anything else in setting tolerable levels of toxic heavy metals in seafood.

A particular case is that of the freshwater fisheries of Canada and the United States, arising out of the mercury contamination of the 1970-1971 period. Based on an acceptable level of 0.5 ppm of mercury, a large part of the fishery catch had to be confiscated. The acceptable limits for certain heavy metals are not confined to freshwater and coastal fish, but also to deep-sea fish, such as tuna and swordfish with natural levels of mercury $\geqslant$ 0.5 ppm.

Dramatic cases of "fish-kills" in coastal areas, owing to the combined effects of pollutants and natural stresses, have been observed frequently. Those in which the direct involvement of a heavy metal has been proven are rare. Roskam (1965) reported a "fish-kill" caused by the coastal discharge of copper sulphate solutions in Holland. In contrast to to these dramatic effects, chronic, heavy-metal pollution is probably even more damaging in the long run. However, the variety of man-produced wastes reaching estuaries and coastal areas makes it virtually impossible to determine the toxic role of heavy metals.

5.3 Human health

Man acquires his body burden of metals through three environmental contacts: air, water and food. These contacts result in a build-up of metals in the body; the average values of such concentrations are given in Table 13.

A number of these metals are integral components of certain body cells, organs or enzyme systems. In such systems some metals are absolutely essential to normal bio-chemical functioning. Other metals, such as mercury, cadmium and lead, are most likely environmental contaminants, since they are not usually detected in infants and are apparently acquired with age. In the case of metals for which there is a nutritional requirement, inadequate quantities can result in deficiency diseases. Metals that are toxic at elevated levels, on the other hand, will result in intoxications with potentially serious consequences (Goldwater *et al.*, 1972). Human diet can vary widely from one area to another in terms of trace elements, leading to situations of deficiencies as well as excesses. Beyond this natural influence, there is the matter of other exposures to trace metals engendered by environmental pollution.

Table 13

Metal contents of "average man" (1)

Metal	Content (mg per man of 70 kg)
Cadmium	20 - 50
Cobalt	1.5 - 3
Copper	72 - 100
Iron	4,000 - 4,200
Lead	18 - 120
Manganese	12 - 20
Mercury	13

(1) From Woolrich (1973).

Those areas from which man harvests food are, all too often, the hardest hit when pollutants are indiscriminately added to natural waters. A case in point is the near-shore and continental shelf which have large populations of edible molluscs, seaweeds, fishes and crustaceans for human consumption.

Mercury contamination has been the basis for one of the major environmental problems that caused an uproar in recent years: the Minamata and Niigata tragedies in Japan (D'itri, 1972). The discharge of mercury into waterways and coastal waters in the form of the element or inorganic salts is known to have been going on for some time. It was generally felt that these discharges were inoffensive. It was then discovered that micro-organisms in the sediments are capable of converting inorganic mercury into organomercuric compounds. These organic compounds of mercury are very toxic by virtue of being able to attack the central nervous systems of organisms.

Cadmium has been implicated as the causative agent in Itai-Itai disease, which has been significant in Japan (Ui, 1972). The disease was attributed to environmental pollution from industries producing or using cadmium. However, there is no documented evidence concerning Itai-Itai symptoms in humans caused by the consumption of seafood. Regarding the effect of other heavy metals on human health through the consumption of seafood, there is no available information.

6. Monitoring and Surveillance

The ultimate goal of marine monitoring is to provide a sound scientific basis for assessing and regulating the release of materials considered dangerous to the marine ecosystem or to man. This goal will also require information on the rates of input of these materials, thus adding another dimension to the monitoring exercises. The steps of such procedures have been summarized by Preston and Wood (1971) in the following terms:

(i) Estimation of pollutant concentration in the sea-water system as a function of the rate of introduction of pollutants.

(ii) Estimation of the concentration factor of the pollutant in the critical material, be it a living organism or sediment.

(iii) Coupling (i) and (ii) leads to an estimation of the concentration of the pollutant in the critical material.

Preston and Wood (1971) also developed the concept of the "critical pathway" approach based on the monitoring of radio-activity in the marine environment. This concept is based on the identification of the most important pathways by which a pollutant can return to man via the marine food chain. According to Goldberg (1976), the identification of these "critical pathways" can lead to more rational monitoring programmes. In this context a good example is perhaps the adoption of fish and shellfish as

indicators of mercury pollution. Most marine fish and shellfish do not appear to be harmed by several tens of ppm (wet weight) of mercury, although man is sensitive to only a few ppm of mercury in his food. Mercury is perhaps one of the few toxic pollutants for which reasonable, accurate and acceptable exposure criteria have been evaluated. Thus, if the major risk of mercury pollution is to man and if he is protected, it is to be expected that marine organisms will be also.

Finally, control programmes, whether designed to have a surveillance role or a monitoring function, will have a basic requirement which is to provide an early warning of danger to man or the specific resource of interest. The need for adequately evaluated control criteria reveals a major gap in present knowledge; without such criteria, monitoring programmes will tend to become exercises that merely accumulate large amounts of numerical data to no purpose.

6.1 Baseline studies

Investigations of the present distribution of certain selected pollutants in the marine environment are known as baseline studies. These studies constitute the basis for future monitoring programmes (IOC, 1974) and are the essential first step to providing data on inputs, distribution and pathways of pollutants.

In principle, all media should be sampled: seawater, organisms, suspended materials, the surface micro-layer and sediments. However, most of the published information on the levels of pollutants in the aquatic environment is mainly related to their concentration in organisms and sediments. The very low concentration of pollutants in the water makes sample contamination a very serious problem; consequently, less reliable information on pollutants in this medium is available.

In the particular case of baseline studies of heavy metals in the aquatic habitat, a great deal of information has been published regarding the levels of these and other elements in tissues of different biotic groups (Portmann, 1972; Bryan, 1973; Preston, 1973; Schulz-Baldes, 1974). Throughout these studies evidence of marked seasonal variations within a species, individual variations, and marked differences according to size (or age) were reported. Two recent studies have identified metals that are accumulating in coastal-zone sediments; some of these metals are being introduced by man, others are not (Erlenkeuser *et al.*, 1974; Bruland *et al.*, 1974 a).

This general information can be considered as baseline data of natural or already modified natural conditions. However, despite the great merit of these investigations, caution should be exercised in comparing these data, because of differences in methodology and of the lack of intercalibration exercises.

6.1.1 Methodology

Although perhaps the least glamorous, the initial steps of trace-metal analysis are usually the most crucial. These steps include the selection of sampling procedures, the gathering of representative samples,

their storage and, if necessary, concentration steps for the final procedure of identification and quantification.

The selection of the analytical technique will be conditioned by the use of the data, as well as by the natural variability in the distribution pattern of the element. Therefore, the problem to be solved is the factor that conditions the sensitivity of the method to be used. The selected methods may differ in their sensitivity, but must be accurate.

It is also necessary to keep in mind that in the particular case of very sensitive analytical techniques, such as anodic-stripping voltametry and flameless atomic adsorption, reagent impurities, dust, glassware, and air entering the laboratories, rather than the instruments, may determine the limits of element detection. Non-destructive techniques, such as neutron-activation analysis and x-ray techniques therefore offer great advantages, particularly in the elimination of impurities. A complete review of recent developments in the analysis of toxic elements in environmental samples has been compiled by Lisk (1974).

6.1.2 Intercalibration

As a consequence of the rapid changes in the use of analytical techniques in the field of environmental chemistry, the concept of standard methods of analysis applied to pollutants was never seriously considered. Thus, procedures for sample collection and preservation, as well as methods for pollutant analysis, vary from one laboratory to another.

Under such circumstances it is essential to carry out inter-laboratory exercises in order to obtain comparable and reliable results. Experience from previous exercises shows that intercalibration depends upon:

(i) Agreement as to comparable methods for sample preparation and analysis.

(ii) Preliminary exchange of carefully prepared standards.

(iii) Joint exercises by the participating laboratories.

Agreement on the methods should not be taken to mean a single method to be used by all laboratories, since this tends to prevent analytical developments and improvements. It is, however, essential that all analytical methods should be intercalibrated to ensure that any variations observed are not due to differences that arise during the analytical stage of the programme. Intercalibration exercises are being carried out by ICES in the North and Baltic Seas, in the North Atlantic, and by the International Laboratory for Marine Radioactivity in the Mediterranean. The ICES intercalibration exercises, which include analysis of heavy metals in water and biological material, have been completed or are in progress. Further exercises are planned for the next three years.

An important element in the success of intercalibration exercises is the preparation of reference samples. The goal for the preparation of standards should be that they contain accurately known amounts of the

substances to be analyzed in their natural matrix. These reference samples should be drawn, if possible, from natural and already modified natural situations in order to provide useful ranges.

With the financial support of UNEP, the International Laboratory for Marine Radioactivity in Monaco has prepared several homogeneous marine environmental samples labelled under natural conditions for world-wide intercalibration in the measurement of heavy metals. These reference materials are oyster-tissue homogenate, copepod homogenate, fish fillet (mullet) and a sea plant. Standard reference materials for heavy metals, such as orchard leaves (NBS-SRM 1571) and bovine liver (NBS-SRM 1577), are available from the National Bureau of Standards of the United States.

Finally, it is desirable that certain national laboratories, headed by recognized leaders in the different fields of marine pollution, research and monitoring, be designated as intercalibration centres for dealing with the joint exercises.

7. Conclusions

Meaningful evaluation of the ecological stresses imposed by man's activities requires improved understanding of the interactions between pollutants and the components of the marine ecosystem.

To understand the cycling of heavy metals in a natural ecosystem it is necessary to identify the major reservoirs of these elements and to determine the mechanisms and pathways of elemental transformation, as well as the rates of elemental turn-over among reservoirs.

The major gaps in our present knowledge can be summarized as follows:

(i) Assessment of the relative amounts of different physico-chemical forms of heavy metal in natural waters, their stabilities, and the inter-conversion processes between these forms.

(ii) Determination of the interaction of variable environmental parameters on reservoir size and transfer rates in the overall system.

(iii) Determination of the biological availability of the different physico-chemical forms to the different components of the marine biota.

(iv) Assessment of the role of micro-organisms as sources of heavy metals for consumer organisms, as producers of toxic organo-metallic compounds, as remineralizers of heavy metals pre-concentrated in plants or animal tissues.

(v) Evaluation of the biological retention of heavy metals by higher marine organisms that are part of man's diet.

(vi) Development of models to describe the present dispersion of heavy metals in the aquatic environment; these models and the calculation of their mass balances are an integral part of monitoring programmes.

This holistic approach and the continuous up-dating of existing sources of heavy metals will provide the most reliable basis for rational management of man's releases of these toxic elements into the marine environment.

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POLLUTION RESEARCH AND MONITORING FOR HYDROCARBONS : PRESENT STATUS OF THE STUDIES ON PETROLEUM CONTAMINATION IN THE GULF OF MEXICO

by A. Vázquez Botello

CONTENTS

1. Introduction

The presence of fossil and biogenic hydrocarbons in seawater, sediments and marine organisms of the Gulf of Mexico has attracted the attention of pollution researchers. Oil-producing activities taking place on the continental shelf in this area have been going on for many years. It is estimated that the coastal area off Louisiana has produced around four billion barrels of oil in the last 35 years (Oppenheimer et al., 1974).

Based on the information gathered at the present time there is a worldwide input of oil to the oceans from offshore drilling and production operations, transportation losses, natural seeps, accidental spills and through waste-water discharges (Table 1). In the Gulf of Mexico, an area of oil production and intensive urban and industrial development, the information on fossil hydrocarbon distribution is still rather limited, particularly from the eastern areas.

In this paper we will try to summarize all available information on the current research carried out in the Gulf of Mexico.

2. Hydrocarbons in the Marine Environment

In the marine environment we generally find a complex mixture of fossil and biogenic hydrocarbons. The difference between these two groups can be established as follows; petroleum hydrocarbons are more complex mixtures with broad ranges of molecular structure and weight. It contains also several homologous series, with an approximate unity ratio between even and odd number alkanes. Marine organisms, on the other hand, have a strong predominance of odd-numbered alkanes. Petroleum contains more kinds of cycloalkanes and aromatic hydrocarbons than the organisms; all the aromatic hydrocarbons in marine organisms are less than one per cent of the total hydrocarbon load.

2.1 Hydrocarbons in the water column

Two main groups of hydrocarbons of biogenic and fossil origin can be found in the water column, those of low molecular weight (C_1 - C_{10}) and those of high molecular weight (C_{11} and up). McAuliffe (1976) points out that methane is the dominant hydrocarbon in the marine environment belonging to the first group, because it is produced naturally by micro-organisms during decomposition of organic matter, and also from oil and gas seeps and offshore oil production.

The concentration of dissolved low-molecular-weight hydrocarbons in waters from the Gulf of Mexico, Caribbean Sea and the North Atlantic has been reported by Swinnerton and Linnenbon (1967), Swinnerton et al. (1969) and Swinnerton and Lamontagne (1974). The concentrations in $\mu g\ l^{-1}$ reported by these authors were: methane, 35.2; ethane, 0.67; ethene, 6.0; propane, 0.67; propene, 2.6; and butane, 0.13. Sackett and Brooks (1975) reported that large coastal areas off the shore of Texas and Lousiana have concentrations of low-molecular-weight hydrocarbons up to six orders of

Table 1

Annual estimates for petroleum hydrocarbons entering the ocean, 1973 and 1980 (1)

Source	Millions of tons per year 1973	1980
Marine transportation	2.2	2.0
Offshore oil production	0.1	0.1
Coastal oil refineries	0.2	0.05
Industrial and municipal waste	0.9	0.6
Urban runoff	1.6	1.9
Natural seeps	0.6	0.6
Atmospheric transport	0.6	0.6
TOTAL	6.2	5.85

(1) National Academy of Sciences (1975).

magnitude higher than those in open-ocean surface waters. These high levels are almost certainly petroleum-derived and come from offshore oil production operations. Other published research in this particular area can be found in Brooks et al. (1973) and Sackett and Brooks (1974). With regard to the presence of low-molecular-weight fossil hydrocarbons from oil spills in the Gulf of Mexico, McAuliffe et al. (1975) determine concentrations up to 200 µg l^{-1} for C_1 to C_{10} hydrocarbons.

The high-molecular-weight hydrocarbons can be considered also in two groups: those in the particulate state; pelagic, beach and abyssal tars; and those dissolved in the water column. Within the first group the so-called pelagic tars are an important part of the high-molecular-weight hydrocarbons present in the waters of the Gulf of Mexico. This is due to the extensive offshore oil production and tanker traffic, as well as to the semi-enclosed nature of the Gulf with weak circulation in its central and western sections (Jeffrey et al., 1974).

Table 2 shows a comparison of pelagic tar concentrations in the Gulf of Mexico and the Caribbean region with those of other areas. Pelagic tar concentrations in the Gulf of Mexico ranged from 0 to 10 mg m^{-2} with an average of 1.20 mg m^{-2}. In the Caribbean, the pelagic tar concentration ranged from 0 to 4.5 mg m^{-2} with an average of 0.74 mg m^{-2}. From the available data it seems that the Gulf of Mexico as a whole has lower concentrations of pelagic tars than the Mediterranean sea and the Sargasso sea. However, the Gulf of Mexico shows a higher concentration of pelagic tars than the Caribbean and about the same concentration as those obtaining in the Gulf Stream. Some of these pelagic tars are swept into the Gulf of Mexico through the Yucatan Strait and out through the Florida Straits by the Loop Current. Most of these pelagic tars originate primarily from shipping and tanker-cleaning operations (Mommesin and Raia, 1975; Brown et al., 1973b).

As in the case of the pelagic tars, other high-molecular-weight hydrocarbons are in dissolved form in the water column. Table 3 shows the results of recent observations in the North Atlantic sea, the Gulf of Mexico and the Mediterranean sea. It is clearly shown that high-molecular-weight hydrocarbons are highly concentrated in the surface micro-layer and decrease with depth.

2.2 Hydrocarbons in sediments

Total hydrocarbon concentrations (fossil plus biogenic) in surface sediment samples cover a broad range between 0.1 to 12 ppt in highly polluted coastal areas, less than 100 ppm in unpolluted coastal areas and deep marginal seas or basins, and between 1 and 4 ppm (mostly biogenic in origin) in deep seas.

There is little information on the concentration of hydrocarbons in sediments from the Gulf of Mexico; most of the published results deal with observations made in coastal areas (Table 4). For other oceanic regions the information is also limited (Kinney et al., 1970; Kinney, 1973). Farrington (ms., 1975) reported on the concentration of hydrocarbons offshore of the New York harbour. Most of the hydrocarbons found in offshore

Table 2

Concentration of pelagic tars in the oceans

Location	Number of samples	Tars mg m^{-2}	Tars-water mg m^{-2}	Mean mg m^{-2}	References
North Atlantic	54	0.12	0.12	0.12	McGown et al.(1974)
Caribbean	64	0.16	0.13	0.26	Sherman et al.(1974)
	20	0.74	0.74		Jeffrey et al.(1974)
Gulf of Mexico	84	1.20	1.20	1.20	Jeffrey et al.(1974)
Gulf Stream	18	3.4	2.7	0.80	Attaway et al.(1973)
	168	0.76	0.6		Sherman et al.(1974)
Sargasso Sea	43	7.5	5.9		Butler et al.(1973)
	11	0.92	0.7		Morris and
	16	7.54	6.0	2.10	Butler (1973)
	25	1.98	1.6		McGown et al.(1974)
	54	2.64	2.64		
	54	1.15	1.15		Sherman et al.(1974)
	86	4.39	3.50		
Mediterranean Sea	663	1.0	0.79	4.1	Horn et al.(1970)
	48	9.7	7.7		Morris et al.(1975)
Pacific Ocean					
West	16	3.8	3.0	3.0	Wong et al.(1974)
East	17	0.4	0.3		
Coastal Area	?	0.0	0.0	0.15	

Table 3

Concentration of hydrocarbons in the water column

Location	Sampling Depth m	Number of samples	Concentration $\mu g\ l^{-1}$	References
Atlantic Ocean (Caribbean, Gulf of Mexico to New York)	10	26	3.5-3.8	Brown et al. (1973)
N.W. Atlantic (Nova Scotia to Bermuda)	0-3 1 5	43 24 24	20.4-60.7 0.8- 1.3 0.4- 0.5	Gordon et al. (1974)
Gulf of Mexico: Galveston Bay	1	1	8.0	Brown et al. (1973)
Louisiana and Texas, Mexico and Caribbean	0-3	9	0.08- 1.1	Parker et al. (1972)
Louisiana and Texas	?	17	0.03- 0.6	Oppenheimer et al. (1974)
Mediterranean Sea	?	4	4-195	Monoghan et al. (1973)
Pacific Ocean	0-3	26	0.2	Cretney and Wong (1974)

Table 4

Concentration of hydrocarbons in sediments from some regions of the Gulf of Mexico

Location	Sampling Depth m	Number of samples	Concentration mg kg^{-1} (dry weight)	References
Louisiana (Coastal areas)	100	2	12 - 140	Smith (1954)
Mississippi Delta	15	4	65	Smith (1954)
Marsh area Mississippi Delta	0.1	1	350	Sever et al.(1972)
Mississippi River	0.4	21	4 - 12	McAuliffe et al. (1975)
Gulf of Mexico Open waters	?	10	12 - 63	Menschein (1969)
Gulf of Mexico: Terminos Lagoon	1-2	7	12 - 56	Botello et al. (1976)

sediments were homogeneously distributed: 10 to 20 ppm in sediments of the continental slope; 40 to 60 ppm in sediments from the continental shelf; and near the New York Bight values up to 2.9 ppt.

At the present time the Marine Science Institute of the University of Texas is conducting an extensive study of the concentration of hydrocarbons in sediments from the continental shelf off the coast of Texas (Parker, 1975).

2.3 Hydrocarbons in marine organisms

The information on the presence of hydrocarbons in marine organisms is even more limited than that on sediments. Marine organisms either make their own hydrocarbons, obtain them from food sources, or convert precursor compounds obtained from their food (Clark and Blumer, 1967). Only a limited number of marine species, from only a few geographical locations, have been analyzed for their native hydrocarbons, usually alkanes and alkenes. It may be pointed out that other classes of hydrocarbons are more prevalent in marine organisms than the limited information suggests.

There is some published information on alkanes in benthic algae and sea grasses from coastal areas of the Gulf of Mexico (Sever, 1970; Attaway et al., 1970; Botello and Mandelli, 1976). There is also some information on the hydrocarbon composition of plankton and invertebrates from the Gulf of Mexico (Parker et al., 1972; Erhardt, 1972; Parker, 1975; Giam et al., 1976; Botello et al., 1976). Some preliminary information on the concentration of PAH's in Crassostrea virginica from several coastal lagoons of the Gulf of Mexico is in the process of publication (Bravo et al., 1976).

Regarding the effects of the fossil hydrocarbons on biological processes, such as photosynthesis, growth and reproduction of marine organisms, the University of Texas, Texas A & M and Florida State University are at present carrying out this type of work with organisms from the Gulf of Mexico (Parker, 1975; Pulich et al., 1974).

3. Conclusions

From the information gathered in the preparation of this paper, it can be concluded that in the Gulf of Mexico at the present time there is a considerable concentration of fossil hydrocarbons originating from offshore oil production and other human activities. When we compare the values obtained in other areas, such as the Caribbean Sea and the North Atlantic Ocean, with those of the Gulf of Mexico, we find that the latter values are high because of the weak circulation in the western and central sections of the Gulf.

So far the number of studies has been very limited. All the countries involved in the Gulf of Mexico and Caribbean need to develop stronger programmes on fossil hydrocarbons as pollutants, particularly as to the short- and long-term effects on the coastal marine biota.

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POLLUTION RESEARCH AND MONITORING FOR HALOGENATED HYDROCARBONS AND PESTICIDES

by E.F. Corcoran

Most of the pollutants that concern man occur in nature; the principal exceptions are short-lived radio-isotopes and chlorinated hydrocarbons. Many pollutants are highly toxic, but are confined to urban and industrial areas; others degrade quickly, while still others are toxic in low concentrations, have a global distribution, and are extremely persistent. Such is the case of the chlorinated hydrocarbons.

The story of the chlorinated hydrocarbon begins with the introduction of the insecticide commonly known as DDT (dichloro-diphenyl-trichloroethane) by Müller in 1939. Although DDT had been prepared by a graduate student in his doctoral studies in 1874, it was not until Müller, who was looking for a moth-proofing compound for woollens, that it became important. Because of World War II, DDT was not put to general use immediately, but was confined to use by the military. It was a boon to combat troops simply to powder with cool, soothing talc instead of bathing in a kerosene concoction and having their clothes autoclaved. The tremendous demonstration of the potential of DDT in the control of typhus (a rickettsial infection transmitted by lice and fleas) and malaria (a protozoan infection of the mosquito that can be transmitted to humans) during World War II earned Müller the Nobel Prize in Physiology and Medicine in 1948. Two other chlorinated hydrocarbon pesticides discovered during World War II were the herbicides: 2,4,-D and 2,4,5,-T. These were destined to become infamous during the Vietnam War.

Soon after the end of World War II, DDT was put to use. This saviour of mankind appeared in all forms: powders, sprays, liquids, aerosols and paints, and was used for all purposes from killing the local ant and roach populations to controlling agricultural production by eliminating pests. After the barns at the Howard Ranch in San Ysidro, California, were sprayed with a white paint containing DDT, flies were carried out by the truckload. But with this overwhelming success with DDT soon came problems. One of these problems was the development of resistant strains of pests. As early as 1947, it was realized that DDT was losing its effectiveness in controlling houseflies (O'Brien, 1967).

Another problem with DDT, because of its broad spectrum of action, was that it caused harm to beneficial species such as bees. Or, by killing a natural enemy, DDT would cause a pest to increase to tremendous numbers. To overcome these problems, other chemicals were developed, until to date there are some 500 chemicals in over 10,000 formulations. Of these 500 chemicals, some of the most persistent and toxic have been the chlorinated hydrocarbons such as benzene hexachloride, heptachlor, dieldrin, endrin, aldrin, methoxychlor, mirex, chlordane and many others. It has been conservatively estimated that, in the past 30 years, about 1.8 million metric tons of DDT alone have been used.

But still another problem was arising - a problem that took some time to recognize but still a problem. Rachel Carson wrote of it in her book "The Silent Spring" and was laughed at for her efforts. She was concerned that the chlorinated hydrocarbons were killing our bird populations. A well-documented example was the killing of robins by DDT used against Dutch elm disease. In this case, the pesticide was concentrated in the food chain from leaf to litter to earthworms to robins. Chlorinated hydrocarbons

were implicated in the decline of several other bird populations through interference with their reproduction (Wurster, 1969; Peakall, 1970) rather than through outright killing. The famous peregrine falcon, which had survived the efforts of farmers, hunters and egg collectors, began a sudden decline in population in the early 1950s. A similar trend also occurred with grebes, woodcocks, bald eagles and ospreys about this same time. An investigation revealed that the cause was related to a drop in the reproduction of the birds. Breeding was delayed, no eggs were laid, or the eggs that were laid were easily broken (Peakall, 1970). The reproduction failures were greatest in the areas where the chlorinated hydrocarbon pesticides were most widely used. These observations spurred several areas of research. The first area of research concerned the thinning of the eggshells. Since then the actual decrease in thickness and weight of eggshells soon after the introduction of chlorinated hydrocarbons has been well documented. Hickey and Anderson (1968) using 614 California peregrine falcon eggshells collected since 1891 showed that these eggshells had a rather stable thickness until the late 1940s and the early 1950s. At this time a sharp drop in eggshell weight was observed (Ratcliffe, 1967). Although this eggshell thinning coincided with the introduction of chlorinated hydrocarbons into general use, it was not until 1974 when Peakall extracted eggshells collected in California and Alaska and found that the presence of DDE (a derivative of DDT) since 1948 correlated with the thinning. Although the loss in weight of these shells has been attributed to interference in calcium metabolism through the inhibition of the enzyme carbonic anhydrase, Pocker et al. (1971) at the University of Washington showed that the chlorinated hydrocarbons, DDT, DDE and dieldrin actually have the ability to coprecipitate minute amounts of the enzyme from solution and thereby reduce enzymatic activity.

Fish also exhibit acute responses to chlorinated hydrocarbon pesticides. An example of this that attracted public notice and caused controversy was a series of fish kills that began in the late 1950s along the Mississippi and Atchafalaya rivers in Louisiana. Catfish and some other fishes hemorrhaged and died in great numbers. Measurement of the waters' pH, dissolved oxygen and temperature gave no indication of the cause of death. An attempt to reproduce the symptoms with viruses, pathogens and toxins was unsuccessful. However, a chloroform extract of the bottom sediments did reproduce the symptoms exactly. The active ingredient in the chloroform extract was later found to be endrin. Another fish kill attributed to endrin occurred in the lower Mississippi river in 1963. Over 5 million fish were killed. Analyses of these fish by the U.S. Public Health Service showed lethal amounts of endrin in the fish tissue. A report by Barthel and others on the monitoring of the Mississippi river and its tributaries in 1967 revealed that the sediments just below an endrin-manufacturing plant contained about 11,000 ppm of endrin, and over 2 ppb in the water. Although no analyses were made on the brown pelican, there has been speculation that the endrin in the fish caused their disappearances from the Gulf Coast in the early 1960s. Sublethal doses have been found in the brown pelican population in Florida by Schreiber (1970). The possibility of the pesticides reaching the estuarine waters was considered quite possible in view of westerly tides which may carry Mississippi river water into Barataria Bay. A study

(Rowe et al., 1971) of the oysters found in several of these bays and estuaries was begun shortly after the great "fish kill" in 1963. In these studies, two chlorinated hydrocarbons, dieldrin and endrin, were measured but the DDT residues, if measured, were not reported. From 1964 to 1966 the median concentration of dieldrin and endrin in oysters was about 10 ppb, while the highest concentrations for these two chlorinated hydrocarbons was 90 and 70 ppb, respectively. By 1969 these concentrations in oysters had dropped to a median of 1.4 ppb of dieldrin and less than 1 ppb of endrin. The water contained less than a part per billion and the sediment from 4 to 5 ppb. By 1969, it was realized that pesticides were present in most of the major river systems in the United States. A network of approximately 100 monitoring stations in operation since 1958 had confirmed this fact.

With the monitoring of rivers and other environmental samples, year after year, dieldrin and DDT and its related compounds were consistently the dominant chlorinated pesticides reported. However, the presence of chlorinated compounds other than these insecticides as residues in environmental samples had been suspected for a number of years. Roburn (1965), in an investigation of a number of wildlife samples, showed that the total content of chlorinated hydrocarbons was greater than could be accounted for by the insecticide, and inferred that other chlorinated compounds were present. Eidelman (1963), in his examination of Norwegian cod liver, reported "compounds in the region of DDE, TDE and DDT" on his chromatograms. The identification of a group of polychlorinated compounds by Jensen (1966) and Jensen et al.(1969) and Widmark(1967) in the Swedish environment first drew attention to the polychlorinated biphenyls as environmental pollutants. About the same time they were found in the wildlife in Great Britain (Holmes et al., 1967), in the Netherlands (Koeman et al., 1969), and North America (Risebrough, 1969). Like DDT, the PCBs were first identified in 1881 and have been manufactured exclusively by the Monsanto Chemical Company since the early 1930s in the United States. PCBs are also produced in Europe, Japan and the USSR.

The major uses of PCBs derive from their high dielectric constant, non-flammability and plasticizing abilities. They are employed as fluids in capacitors and transformers, as hydraulic fluids and heat-transfer liquids. As a plasticizer, PCBs have found use in adhesives, sealants, automobile tyres, brake linings, paints and printing ink. Like DDT sales, the PCBs steadily increased, and in 1970 were estimated at 34,000 tons (Hammond, 1972). Monsanto was reluctant to reveal the production figure, but pressure from environmentalists, as well as evidence of universal contamination, caused Monsanto not only to reveal production figures, but to phase out the use of PCBs in heat-transfer systems, to discontinue the production of some highly chlorinated PCBs, and to confine the use of PCBs mainly to closed electrical systems.

Since 1971, Monsanto has restricted the use of PCBs, yet like the chlorinated hydrocarbon insecticide, they have become ubiquitous in the world's waters. PCBs are very stable, resist degradation by natural environmental forces, have small but finite vapour pressures and are practically insoluble in water (Chan, 1972). These properties ensure their persistence after the manufactured product becomes a waste product. Once

in the environment PCBs appear to behave like DDT in their movements through the ecosystem (Risebrough, 1968, 1969; Chan, 1972).

Once PCBs were identified they were found in most of the environmental samples analyzed. Researchers at Woods Hole measured high levels of PCB in plankton samples, and found that open-ocean levels were 10 - 100 times higher than those observed in coastal plankton. Also, plankton contained more PCB than did the fish, indicating that both received PCB directly from the water (Holden, 1970). The growth of diatoms was inhibited (Mosser et al.,1972) PCBs are often toxic to crustaceans, molluscs and fish at concentrations of just a few parts per billion (Duke et al., 1970; Hansen, 1972). Much of the information on the toxicity of the PCB, Aroclor 1254, was summarized from the research done at the Gulf Breeze Laboratory during the past 7 years for the House Committee on Merchant Marine and Fisheries (1976). After discovering a leak of Aroclor 1254 at the Monsanto plant in 1969, Duke and his associates monitored the environment and did laboratory studies to determine the effects of Aroclors 1016, 1242 and 1254 on, and bio-accumulation by, estuarine organisms. They concluded from their field studies that polychlorinated biphenyls: i) do occur in the marine environment; ii) are readily dispersed from point sources; iii)are persistent; and iv) are concentrated in animals, plants and sediments; and from their controlled laboratory studies that: i) various PCBs are toxic (at the parts per billion level in water) to shrimp, fish and other organisms; ii) animals can obtain PCBs from water, sediment or food organisms; and iii) these chemicals are bio-accumulated.

It is well known that both the chlorinated hydrocarbon pesticides and the PCBs have reached all parts of the marine environment (Risebrough et al.,1968a, 1968b, Frost, 1969). Bidleman and Olney (1973) confirmed their widespread distribution in the Sargasso Sea, and Harvey with others (1974) showed both the industrial PCBs as well as DDT residues were to be found from 66°N to 35°S latitude. In an attempt to explain how the compounds reached the sea, and knowing that the Mississippi river drains two-fifths of the land area of 48 states as well as passing through one of the regions of heavy pesticide use at its southern end, Corcoran and Lee (1970) studied the chlorinated hydrocarbon concentration of the waters entering the Gulf of Mexico, the river and Gulf sediments and the benthic organisms. While some entered the Gulf of Mexico from the Mississippi river, most of the pesticide was lost to the sediment. Once in the sediments, they can be concentrated by benthic organisms, taken up by fish or brought to the surface by stirring or rooted vegatation. From the surface, the chlorinated hydrocarbons can be concentrated into slicks (Seba and Corcoran, 1969) from which birds feeding on organisms below the slick can receive large dosages of the chlorinated hydrocarbons, or the chlorinated hydrocarbon can vapourize and co-distill into the atmosphere. Dr Edward Baum (1974) states: "Pesticides are usually introduced into the atmosphere as aerosol sprays or volatile gases", while Frost (1969) says, "The pesticides also vapourize as a result of their tendency to accumulate at the surface of the water where they are carried off into the atmosphere as the water evaporates". Using DDT production figures and assuming rainfall to be the dominant method of removal from the atmosphere, Woodwell et al. (1971) estimated the atmospheric residence time for chlorinated hydrocarbons to be 3.3 years. In a study of the Bermuda area of the Sargasso Sea, Bidleman and Olney (1973), making the assumptions that: i) PCB has a constant

concentration in the tropopause; ii) PCB is uniformly distributed in the upper 100 metres and has a residence time of 4 years (Broecker, 1963); and iii)the major source of PCB input into the ocean is via the atmosphere, have estimated that the residence times for PCB and DDT are between 40 and 50 days, or about 20 times shorter than previously estimated. In two recent still unpublished studies, McClure and LaGrange have shown the half-life in the troposphere of aerosol, high-boiling-point hydrocarbon is about 5 hours. Consequently, the atmosphere cannot be considered to be a large reservoir for these pollutants. They also found that dry deposition accounts for the majority of the chlorinated hydrocarbon fallout. Hence, this could lead to severe local contamination of land areas (within 100 km) before atmospheric transport would produce global contamination. "On the other hand, a pollutant entrained in an ocean current could easily have started its journey from an urban area as an aerosol." Thus, the global transport of chlorinated hydrocarbons to the remote areas of the globe is probably by ocean currents or possibly by migrating birds or animals.

Now after having had chlorinated hydrocarbon pesticides with us for 30 years and the polychlorinated biphenyls for over 40, we are still plagued with their presence. As Duke at Gulf Breeze will testify, the leak of PCBs into the environment has been corrected for about 7 years, but two oyster beds located 8 miles from the original source, still contain measurable amounts of PCB. Although the lower Mississippi river bottom is devoid of organisms except for an occasional wormtube (Corcoran and Lee, 1970), a condition confirmed by the author in 1975, the oysters in Barataria Bay and adjacent estuaries are still contaminated from earlier spills. Some years will go by before a kepone-free* fish can be obtained from the James river and certain parts of the Chesapeake Bay. But what about us? Will we be like the birds: a declining population, from eating food with sub-lethal concentrations? After all, it has been just a little over a generation since the first introduction of chlorinated hydrocarbons. What are some of the questions we must ask ourselves?

Do the chlorinated hydrocarbons bio-accumulate? There is evidence for both sides of the question. Much more research is needed here.

Do the PCBs and the chlorinated hydrocarbon pesticides move through the environment in the same manner? George Harvey and his associates say no.

Has technology kept pace with the need to measure minute quantities of chlorinated hydrocarbons in our environment? The gas chromatograph was developed with an electron-capture detector capable of measuring picogram quantities. When dieldrin could not be separated from the pp^1 DDE the column coatings OV-17, QF1, etc. were developed. Interference of the sulphur and BHC was eliminated with copper treatment. Precisely deactivated absorbents can be used to separate PCBs and other chlorinated hydrocarbons. Confirmation of findings can be done by mass spectrometry, coulometry, liquid chromatography and thin-layer chromatography.

Can chlorinated hydrocarbon research and monitoring be done in developing countries? An excellent study was just completed by Duursma in Indonesia (Duursma, 1976).

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* Kepone is a chlorinated hydrocarbon insecticide (C_{10} Cl_{10} O) also known as Chlorodecone.

What is the best way to collect samples for chlorinated hydrocarbon analyses? A recent unpublished paper by McClure, Scura, Theilacker and Rommel shows an association between chlorinated hydrocarbons and colloids. This paper will cause us to re-examine all our collecting techniques.

What are we as scientists going to do about the bromates formed in the sea by the heavily halogenated sewage effluents?

What is the greatest need for scientists studying chlorinated hydrocarbons in the environment today? The greatest need is for a method of quickly determining the total concentration of chlorinated hydrocarbon in the environmental samples, because it is the total amount that affects the organisms - not DDT alone, nor PCB, nor endrin, but their collective influence.

These and many others are questions we must face and answer; as Risebrough said: "The continuing need is for solid data that will answer the pertinent questions, and for impartial, independent interpretations of these data by scientists who employ a variety of methods and approaches and whose conclusions are not influenced by political or commercial considerations".

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POLLUTANT TRANSFER AND TRANSPORT IN THE SEA

by G. Kullenberg

Notations

A	vertical turbulent transport coefficient for momentum
C	concentration of contaminant
c	surface wave phase speed
c_d	drag coefficient
f	Coriolis parameter $\equiv 2\omega_o \sin\varphi$
K_x, K_y, K_z	turbulent diffusion coefficients in the x, y, z directions, respectively
$N=\left(-\frac{g}{\rho}\frac{d}{dz}\right)^{\frac{1}{2}}$	Brunt-Väisälä frequency, or stability frequency
q	horizontal current vector
Ri, Rf	gradient and flux Richardson number, respectively
t	time
u_*, u_*^a	friction velocity in water and air, respectively
u, v, w	velocities in the x, y, z directions, respectively
u', v', w'	fluctuating velocities
W_a	wind velocity
x, y, z	orthogonal coordinate axes; z positive upwards
ε	rate of energy dissipation per unit mass
κ	von Karman constant
φ	latitude
ρ, ρ_a	water and air density, respectively
ω_o	angular velocity of the rotation of the earth
τ	internal stress
τ_o, τ_b	wind stress and bottom stress, respectively
σ_x^2, σ_y^2	longitudinal (x-direction) and lateral (y-direction) variances of a horizontal concentration distribution, respectively

CONTENTS

1. Introduction

The dispersion of a dynamically passive contaminant by natural physical processes is considered. By dispersion we mean the total effect of different processes acting to produce uniformity in the spatial distribution. There are two main classes of processes responsible for the dispersion:

i) advective (or convective), implying transportation of the contaminant, thereby causing a local change in the concentration;

ii) diffusive, implying a random local exchange of the property (water) without causing any net transport of water.

Absolute dispersion is the dispersion observed relative to a fixed origin, one-point dispersion. When the dispersion is observed relative to a moving origin it is called relative dispersion (two or more particle dispersion).

In principle only molecular diffusion should constitute class (ii). However, in order to determine the advection, a complete knowledge of the field of motion is required. Since this cannot be achieved, at present, we are forced to define averages over certain time- and space-scales. These averages determine the advection, and the fluctuations around them determine the diffusion. The definition of the time and space scales must to a certain extent depend upon the specific problem or area at hand. A proper scaling of the problem at hand is often crucial. In Table 1 some basic scaling parameters common on oceanography are summarized. It would lead too far to discuss them here.

The physical dispersion of pollutants is influenced by such environmental factors as:

wind, surface waves

radiation (incoming and outgoing), convection, evaporation and precipitation

salinity, temperature and density (or bouyancy) distributions

currents and current distributions, including tides and other rotational effects

turbulence (which in this paper always means three-dimensional turbulent motion), internal waves

In addition to these usually highly interrelated physical factors come the chemical and biological factors and their interactions. In this paper some of the effects of physical factors on the dispersion will be discussed. The flocculation process and other chiefly chemical effects of the salinity and temperature will not be discussed. Suffice it to mention that laboratory experiments have demonstrated that flocculation considerably influences the gravitational settling velocity of the solid material contained in sewage sludge (12). A settling velocity of the order of 1 metre per hour seems to be representative for the flocculated state. In the surface layer of the sea the turbulent transport will effect a vertical

Table 1. Some common scaling parameters.

Type	Parameter	Scaling
Boundary layers		
planetary	thickness H'	$H' \sim u_*/f$
Ekman	thickness D	$D \approx \kappa \frac{u_*}{f}$
constant stress	thickness h'	$h' \approx 0{,}2 \sqrt{c_d} \cdot \frac{u_*}{f}$
Monin-Obukhov	length[1]	$L = \frac{u_*^3}{\kappa \overline{B(0)}}$
wind-mixed layers	thickness h	$h \approx u_* \sqrt{t \cdot N}$ (for small times t) maximum $h_{max} \approx 2 \frac{u_*}{\sqrt{fN}}$
Turbulence		
baroclinic instability	Rossby radius R	$R = \sqrt{g'H}/f$ (H ≡ water depth)
rotation-buoyancy	lenght λ_b	$\lambda_b = \left(\frac{\epsilon}{f^3}\right)^{\frac{1}{2}}$
buoyancy-inertia (Ozmidov scale)	length λ_N	$\lambda_N = \left(\frac{\epsilon}{N^3}\right)^{\frac{1}{2}}$
inertia-viscosity (Kolmogorov scale)	length λ_r	$\lambda_r = \left(\frac{r^3}{\epsilon}\right)^{1/4}$

1) $B(z) = -g \cdot \frac{\overline{w'\rho'}}{\rho_o}$ is the buoyancy flux.

cont.

cont. Table 1.

Type	Parameter	Scaling
Transfer coefficients		
neutral conditions	K_z, A	$= - \varkappa u_{*} z$
very stable	A	$= - \varkappa u_{*} LRf$
very stable	K_z	$= - Rf \cdot \epsilon \cdot N^{-2}$

spread at least one order of magnitude larger than this. In deep layers and in stratified fjords and enclosed seas, the vertical transport due to mixing can often be of the same order as, or less than, that due to the gravitational settling.

The aim of this paper is not to produce a list of formulae which may be used to predict dispersion. Some such formulae do exist, but they are often semi-empirical and have only been partially verified by observations of a local character. Consequently they must be used with great caution. Rather, the aim is to discuss various factors in the sea in relation to dispersion. Despite considerable progress in the last decades on the problem of dispersion in the sea, we can only parameterize and predict the dispersion in a few simplified situations. In many cases we do not know the dispersion process, and cannot formulate the proper forcing functions, much less predict the response.

2. General Considerations

2.1 Partition of the ocean environment

Most parts of the ocean, including the shelf areas, are characterized by a relatively stable density distribution. As a consequence, the turbulence in the ocean is much weaker than in the atmosphere, and the wave motion plays a very important role. Considering these two characteristics of the marine environment, it is pertinent to divide the water column into four different layers:

i) the surface boundary layer where atmospheric effects dominate;

ii) the pycnocline (thermocline and/or halocline) layer where the buoyancy effects dominate;

iii) the deep-water layer where internal waves are very important and turbulence occurs intermittently.

iv) the bottom layer where bottom friction dominates.

Furthermore, it is often necessary to give special consideration to regions such as upwelling areas, estuaries, fjords and enclosed seas, where local features can determine the conditions.

2.2 Dispersion model

The dispersion can be studied by various equations and models. In many cases the so-called advection-diffusion equation is used, here assuming a passive contaminant:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} - \frac{\partial}{\partial x}\left(K_x\frac{\partial C}{\partial x}\right) - \frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right) - \frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right) = \Sigma \qquad (1)$$

Here C is the concentration, u, v, w are the current velocities and K_x, K_y, K_z the turbulent mixing coefficients in the x, y, z directions, respectively. The term Σ includes sources and sinks as well as interaction

phenomena when more than one substance is present. Here conditions influencing the left-hand side will be discussed.

2.3 Scale effect

The horizontal motion in the sea covers scales ranging from those of oceanic circulation to molecular ones. Long time-series of current measurements (e.g. 16, 21, 22) show that the tidal and inertial motions have high energy levels. The peak corresponding to the inertial period is often conspicuous in the power spectrum. In general it has not been possible to resolve longer-period oscillations. The possible existence of such oscillations is of great importance for the dispersion efficiency of an area.

As for the short-period fluctuations, the energy density decreases rapidly with increasing frequency; Webster (70) found an energy decrease conforming with the -5/3 law for periods less than 6 hours.

Consider now the relative dispersion of a cloud of a passive contaminant on the surface or in an internal layer where the vertical gradient of the horizontal current (i.e. vertical shear) is negligible. Then the scales of motion much larger than the cloud will transport it as a whole. These are the advective scales. The scales of motion much smaller than the cloud will act in a diffusive way to homogenize the distribution inside the contaminated area. The scales of the same order of magnitude as the area will distort it and create a larger area for the smaller scales to act on. The diffusive efficiency, defined as diffusivity contribution per unit kinetic energy (11), is largest for the small scales. These contain very little energy whereas the bulk of the energy is contained in the large scales. This implies that the efficiency of the turbulent diffusion will increase as the size of the contaminated area grows, until it is of the same order of magnitude as the largest energy-containing scales present in the particular region. Beyond this no significant increase of the effective diffusion with the scale can be expected. The time-dependence of the spreading can be determined by giving the variance of the concentration distribution vs. time. For the rotationally symmetrical variance σ_r^2, defined by

$$\sigma_r^2 = \frac{\int_0^\infty r^2 \cdot 2\pi r\, C dr}{\int_0^\infty 2\pi r\, C dr}$$

several studies suggest that $\sigma_r^2 \propto t^2$. Here r is the equivalent radius for the concentration isoline C. This is in good agreement with the theoretical result of Joseph and Sendner (76) giving

$$\sigma_r^2 = 6P^2t^2 \qquad (2)$$

where P is the horizontal diffusion velocity. Very often a horizontal diffusion coefficient K_h is introduced together with a length scale l_h,

$$K_h = \sigma_r^2/4t, \qquad l_h = 3\sigma_r$$

The functional dependence of the horizontal diffusion coefficient K_h on the scale l_h has been found on observational grounds to be

$$K_h = c\, l_h^{\,n} \qquad (3)$$

Recently reported values of n and c are given in Table 2.

The similarity laws of turbulence (1) predict

$$K_h = \text{constant}\ \varepsilon^{1/3}\, l_h^{\,4/3} \qquad (4)$$

where ε is the rate of energy dissipation per unit mass. The value 4/3 of n is in agreement with the well-known Richardson law (57). It cannot be concluded that the assumptions behind the similarity laws are fulfilled in the case of ocean turbulence simply because the empirical value of n is close to 4/3. On the contrary, these assumptions cannot be expected to hold in the stratified sea over the large range of scales under consideration. Ozmidov (52, 53) pointed out that the energy is supplied on a few typical scales, namely: at atmospheric (global) pressure distributions, of the order 1,000 km with energy influx per unit mass $\varepsilon \approx 10^{-5}$ cm^2 sec^{-3}, the tidal and inertial oscillations, of the order 10 km with $\varepsilon \approx 10^{-3}$ cm^2 sec^{-3}, and the surface gravity waves of the order 10 m with $\varepsilon \approx 10^{-1}$ cm^2 sec^{-3}. The scale interval between these input scales is so large that, Ozmidov speculated, the turbulence may become isotropic by the cascade process.

In many coastal and shallow water areas, tidal oscillations, together with local winds, are the important energy sources. The range of scales covered by these motions is limited; furthermore the coast will prevent the formation of large-scale, fluctuating motions. This implies that the contaminated area will reach a critical size after a relatively short time, beyond which no significant increase in the effective diffusion will occur. This situation is illustrated by large-scale dye experiments described by Talbot (63) in the North Sea. Kullenberg (34) compiled several sets of data from shelf seas and found that for scales larger than a few kilometres the value of n decreased noticeably (Fig. 1). Similarly, in the Baltic the value of n appears to be one for sub-surface layers. It should be noted that this applies to coastal waters and shelf seas. Several authors have suggested that a constant, scale-independent, effective diffusion coefficient should be used in coastal waters, especially when the absolute dispersion relative to a fixed point-source is considered (e.g. 10, 25).

Inertial currents, i.e. horizontal oscillations with a period of $\pi/\omega_o \sin\varphi$, are very promiment features in many stratified waters some distance from the coast. They are generated by meteorological forces (56), most effectively by winds with periods less than the inertial period. The inertial motions are built up in the surface layer of stratified waters and penetrate gradually to deeper layers. They do not change phase with depth.

In near-neutral conditions the wind energy seems to act on the whole water column. Gascard(20) studied this situation in the European Mediterranean and demonstrated that stability oscillations were then

Table 7. Recently reported results on the relation between the apparent horizontal diffusion K_h and the horizontal length scale l_h.

Reference	Area, depth	Range of l_h (cm)	Exponent n	Coefficient c	Number of data points
Okubo (44, p.70)	Ocean, surface	10^3 -10^9	1.1	0.11	6
Okubo (44, p.90)	Ocean, surface	10^3 -10^9	1.19	$2.3\ 10^{-2}$	27
		10^3 -10^6	1.23	-	8
Okubo and Ozmidov (49)	Ocean, surface	10^3 -10^9	1.33	$(2.3\text{-}0.6)10^{-3}$	-
Okubo (47)	Ocean, surface	10^4 -10^7	1.15 *	$1.0\ 10^{-2}$	57
Kullenberg (33)	Coastal, subsurface	10^3 -10^5	1.31	$1.3\ 10^{-3}$	21
Kullenberg (34)	Coastal and open sea, subsurface	10^3 -10^5	1.21	$3.0\ 10^{-3}$	46
Kullenberg (34)	Coastal and open sea, surface and subsurface	10^3 -10^7	1.32	$1.1\ 10^{-3}$	59

* Not determined by least square fitting.

important, with a period corresponding to the Brunt-Väisälä frequency N. In such situations, strong, depth-penetrating vertical motions occur.

In stably stratified waters, which is the most common condition, the vertical motion is very small and the vertical convective term in eq. 1 is usually neglected. The effect is included in the vertical diffusive term.

In stratified conditions the turbulence can become fully suppressed and the motion transformed to wave motion, internal waves. They influence the vertical position of a contaminated layer by the oscillation, but effective mixing in this case only occurs when the waves break. It appears that an instability of an internal wave field is often due to shear instability. A relevant criterion for the existence of turbulence is then the Richardson number criterion: when $Ri > 1/4$ in the whole water column the motion is stable (no turbulence).

The discussion so far about the spreading cloud is applicable when there is no vertical shear in the contaminated layer, or when the contaminant is fixed at the surface. When there is shear the vertical shear effect will influence the dispersion of the contaminant. The shear effect is the combined action of vertical diffusion and vertical shear, generating an apparent horizontal diffusion. This mechanism is very important in many areas, both coastal waters and open seas. Then it can be expected that oscillating horizontal motions with shear will affect considerably the spreading, even when the scales of the motions are larger than the cloud (34).

The separation between advection and diffusion must be considered from case to case. It is quite clear that the oscillations of the motion are of central importance for the dispersion, and the average, or residual, current is not necessarily a good measure of the dispersion.

The layers defined above will now be discussed separately.

3. The Surface Boundary Layer

This layer is influenced by the wind and wind-generated waves, radiation, convection, precipitation and evaporation. Its thickness is determined in most areas by a balance between the mechanical mixing induced by the wind action and the sources of negative buoyancy operating at the surface. The rotation of the earth is in general important, implying that the wind current changes both magnitude and direction with depth.

3.1 Wind and waves

The wind transfers momentum to the sea by turbulent air motion. Phillips (54) demonstrated that the momentum flux to long waves ($c > 5u_*^a$) is a small fraction of the total transfer. The molecular viscosity and drag induced by short waves seem to dominate the transfer process. The wind stress is usually given in the form

$$\tau_0 = \rho_a c_d W_{10}^2 \qquad (5)$$

where ρ_a is the air density, c_d the drag coefficient, and W_{10} the wind speed at 10 m. Recent observations suggest that $c_d = (1.3 \pm 0.3)\ 10^{-3}$ for $5 \text{ m sec}^{-1} \leq W_a \leq 20 \text{ m sec}^{-1}$ (30), and that the height of observation of the

wind speed is not critical. Since the momentum transfer to short waves dominates, the drag is practically independent of the mean square height of the waves and the fetch. The energy flux to long waves, on the other hand, is considerable. It can be of the same magnitude as, or larger than, the energy flux to the wind-induced current (54). It should be pointed out that the processes active in the transfer are not yet well understood.

The transfer of momentum from the air results in the generation of turbulence and drift currents. In general the turbulence will penetrate down to the first density interface, the depth of which depends upon the strength and persistency of the wind, as well as upon the buoyancy flux at the surface. The penetration to the top-most interface (pycnocline) is usually rapid, a matter of hours for winds above 4-5 m sec^{-1}. The deepening of the mixed layer, however, is a much slower process.

A considerable amount of turbulence is generated by the breaking of the waves, and an intricate problem is the relative importance of the wave-induced and the directly wind-induced turbulence. This question has not yet been resolved. It seems that the wave-generated turbulence is concentrated near the surface (61). It appears that this type of turbulence penetrates very little into the deeper layers. Investigations by means of dye and floats in the surface layer suggest that the dispersion is stronger in the top few metres than in the deeper parts of the surface layer (48).

Several aspects of the surface wave dynamics are of importance for the dispersion (54, p.33 f).: The particle orbits are not exactly closed causing a mass-transport. The influence of the molecular viscosity gives rise to an additional shear which adds to the mean vertical shear. On a contaminated surface the attenuation of the short waves is greatly increased. This provides an inward force at the edges of a large slick helping to maintain its coherence, whereas the net force is large enough to transport a small slick in the mean direction of the short waves. In water of limited depth the friction in the water induces a mean forward velocity near the bottom, which is significant in problems involving the sand or sediment transportation by wave action.

The surface layer can also be mixed by wind-induced cellular motion called Langmuir cells. The generation mechanism as well as the depth of penetration of these cells are debatable. Most evidence (e.g. 80) suggests that the penetration is limited to the top 10 metres. The cells are observed for winds about 4-5 m sec^{-1} when foam lines are formed in the convergences; downwelling velocities in the range 1-10 cm sec^{-1} have been reported, but reliable observations are very difficult to obtain. The upwelling is more diffuse, spaced between the lines of convergence.

3.2 Vertical transfer coefficients

In the surface layer the vertical turbulent eddy viscosity A can be related to the wind force as done by Ekman (14; 62), who found the relation

$$A = 7.3\ 10^{-5}\ W_a^{\ 2}\ (cm^2\ sec^{-1}),\ \text{where}\ W_a > 5\ m\ sec^{-1}. \qquad (6)$$

(The numerical coefficient has been recalculated by the present author using the new values of the drag coefficient cited above) whereas Kullenberg (34) found

$$A = 4.1\ 10^{-5}\ W_a^{\ 2}\ (cm^2\ sec^{-1}),\ \text{where}\ W_a \geq 5\ m\ sec^{-1}. \qquad (6a)$$

Turner (66) considered the energy budget of the wind-mixed surface layer, observing the local changes of the temperature structure and deepening of the thermocline over some hours in the open sea. He related the observed changes to the energy input from the wind and found that this was considerably larger than $u_*^a \cdot \tau_o$, but that only part of this energy was used for mixing across the density interface. The energy input from the wind can be expressed as $V_o \cdot \tau_o$ where V_o is the wind current velocity at the surface. This is very nearly 2% of the wind speed. Several authors have subsequently confirmed that only a small fraction of the energy transferred from the wind to the water is consumed in vertical mixing.

The vertical turbulent diffusivity K_z has also been related to the wind force, but the scatter in the observations is large. For a wind force above 4-5 m sec^{-1} Kullenberg (31) found $K_z \propto W_a^{\ 2}$ using observations from sub-surface dye experiments, whereas Bowden et al.(7) found $K_z \propto W_a^{\ 3}$ using dye observations in the top few metres. The difference in results could be explained by the enhanced dispersion in the top metres because of wave action. A representative range of K_z in the wind-mixed layer in shelf seas is 5-50 $cm^2\ sec^{-1}$. In very strong winds and near-neutral conditions larger values of K_z can be expected, of the order of 100 $cm^2\ sec^{-1}$. Only in homogeneous conditions can it be expected that $K_z \approx A$. In stratified conditions $K_z < A$.

Since considerable scatter has been found in the relation between A and the wind speed, it has been suggested (72) that the eddy viscosity is related more to the wave spectrum than to the wind itself. This question has yet to be resolved. The semi-empirical relations between A and W_a can in any case be used to estimate A.

3.3 Vertical shear effect

The development of the wind current involves time scales of the order of days. The wind current effects dispersion both by advection and mixing. The shear in the wind current system is considerable, and the vertical shear effect is an important dispersion mechanism in many areas. The shear results from wind currents, slope currents, tidal currents, and wave effects. The vertical shear is an extremely important dispersion parameter. The form of the current spectrum is also of great importance, and the characteristic periods of the currents in an area should always be investigated.

There are two different regimes of the shear effect: (i) The case when the contaminant is occupying an internal unbounded layer; then the effective horizontal diffusion is proportional to the vertical diffusion coefficient K_z. (ii) The case of a layer bounded by two impermeable horizontal boundaries; then the effective diffusion is inversely proportional to the vertical diffusion coefficient.

Bounded case : Bowden (5) and Okubo (45), among others, treated the bounded case, considering a current field consisting of a uni-directional steady current with a superimposed oscillating component in the same direction. The amplitudes were functions of the depth z. They predicted that in a stable density gradient when K_z is decreased, the horizontal dispersion is increased since $K_x \propto K_z^{-1}$. Bowden considered the shear effect to be important for relatively small scales, up to about 10 km. For larger scales the purely horizontal turbulent mixing would be the dominant factor.

Unbounded case : The unbounded case has been studied for instance by Carter and Okubo (9), Okubo (45) and Kullenberg (33, 34). Carter and Okubo included steady vertical and horizontal shears in a uni-directional current field, U. They incorporated the small-scale motion by means of effective horizontal diffusion coefficients as well as vertical diffusion. They found that the shear terms, being proportional to t^3, will dominate the longitudinal variance already at small diffusion times. The variance is proportional to the square of the shear. It is noted that with this formulation no shear effect is obtained in the lateral direction.

Kullenberg (33) considered a model with a steady, depth-dependent current and a superimposed oscillation with a longitudinal and lateral component. The amplitude was variable with depth but the phase and period were constant. The mixing due to the small-scale horizontal turbulence was neglected, an approximation based on observational evidence; K_z, as well as the vertical shears, were treated as constants in the layer under consideration. The model was found to give a reasonable prediction of the horizontal diffusion (Fig. 2). In the Figure data have been used from experiments by the author (34) and from the large-scale experiment RHENO (71) in the North Sea. Scales up to about a week are covered. The result clearly demonstrates the dependence of the dispersion on the vertical current shear and the oscillating current components. When two oscillating components are included in the model it is found that the oscillation with the largest period is most important, provided the gradients of the amplitudes are the same. In many cases in the field, however, the low frequency oscillations tend to have relatively small vertical variations.

Usually, the horizontal concentration distribution in a shear flow is asymmetrical and $\sigma_x^2 > \sigma_y^2$. This implies that the effective horizontal diffusion coefficient is not symmetrical. In general, rotationally symmetrical models should be avoided for the interpretation and prediction of diffusion in coastal waters.

The importance of the vertical shear effect has also been demonstrated by Talbot (63) for waters around Great Britain. It is more difficult to ascertain experimentally the influence of the horizontal shear effect, largely because it is extremely difficult to measure the horizontal current gradients. Most recent investigations suggest that the vertical shear effect is dominant for scales up to about a week, but no doubt the horizontal shears will become important over larger time scales.

3.4 Buoyancy generation

A number of processes operating at the surface will generate a net flux of buoyancy across the surface. This buoyancy flux is in most cases negative, and will tend to create a stable stratification which absorbs the mechanical turbulent energy generated by the wind action. The thickness of the wind-mixed layer as a function of the wind force was deduced by Kitaigorodsky (28) for open-sea regions. He found that the thickness would increase from 10 m to about 30 m for a wind increase from 5 m sec^{-1} to 10 m sec^{-1}.

Turner and Krauss(68) developed a one-dimensional model for the seasonal thermocline disregarding advection and rotation. They demonstrated that the thermocline depth is determined by a balance between the locally wind-induced mixing and the heat input. The wind stirring was shown not to penetrate beyond the topmost density interface. Since both the heat input and the wind force can vary over the warm season, several density steps can be generated and preserved in the water column until the cooling season.

Phillips (54) found, by means of similarity arguments, that for small times the layer thickness is proportional to the time t. On the other hand, laboratory experiments by Kato and Phillips (27) suggested that the increase of the mixed-layer thickness due to erosion of the underlying stable pycnocline layer is proportional to $t^{1/3}$. In a recent study, de Szoeke and Rhines (79), demonstrated the existence of several asymptotic regimes for the deepening of the wind-mixed layer. After an initial linear rate of deepening, further deepening by erosion follows at a rate $\propto t^{1/3}$, which in turn is transformed into a regime where the generation of turbulent energy at the base of the layer is important and the rate of deepening $\propto t^{1/2}$. After about one-half pendulum day this regime breaks down and erosion takes over again. It should be pointed out that the density interface is not destroyed by the erosion, but is gradually sharpened and forced downwards.

3.5 Vertical mixing in stratified conditions

Often a shallow mixed layer, 5-10 m deep, is followed by a gradual increase of density towards the pycnocline. In stably stratified waters the vertical component of the turbulent motion is suppressed. This means that the turbulence is weakened, since the production of turbulence is coupled to the existence of a vertical component (60). In such conditions the vertical mixing is strongly decreased.

The Richardson number and the ratio K_z/A: The momentum transport is not suppressed as much as the mixing of a passive contaminant, implying that $K_z < A$. The ratio K_z/A is then of great interest and has been subject to many theoretical studies and experimental investigations, most of them in the laboratory. It is generally found to be a function of the gradient Richardson number, Ri,

$$Ri = -\frac{g}{\rho}\frac{d\rho}{dz}\Big/\left(\frac{dq}{dz}\right)^2 = N^2\Big/\left(\frac{dq}{dz}\right)^2 \quad , \; z \text{ positive upwards}$$

where ρ is the density and q the horizontal current vector. The symbol N represents the stability frequency or the Brunt-Väisälä frequency.

Munk and Anderson (39) found the relation

$$K_z/A = (1 + 10\ Ri)^{\frac{1}{2}} / (1 + 3.33\ Ri)^{3/2} \qquad (7)$$

which has been much used. It was found to compare reasonably well with recent observations in the Mersey Estuary (6).

The flux Richardson number, Rf, is defined as the ratio between the energy absorbed by the buoyancy forces and the total available turbulent energy; therefore,

$$Rf = Ri \cdot (K_z/A) \qquad (8)$$

In the stable conditions (Ri > 0.1) encountered in many areas of the sea, the ratio K_z/A is well approximated by a relation of the form

$$K_z/A = Rf_c/Ri \qquad (9)$$

where $0.15 \geq Rf_c \geq 0.05$. The critical value Rf_c of the flux Richardson number is the value reached by Rf when the turbulence is fully suppressed.

Ellison (15) investigated the conditions in the atmospheric boundary layer and deduced the relation

$$\frac{K_z}{A} = \frac{(K_z/A)_o\ (1-Rf/Rf_c)}{(1-Rf)^2} \qquad (10)$$

where $(K_z/A)_o = 1.1$ and is the ratio in neutral conditions. This relation follows the trend found in laboratory observations and in the few existing field observations quite well.

The gradient Richardson number, Ri, is a very important parameter. Usually a meaningful overall type of Ri-number ($\overline{Ri}$) can be determined from observations with a vertical resolution of 1 to 5 m; commonly $\overline{Ri}$ is in the range 0.1 - 10.

Vertical mixing related to environmental conditions: Several investigators have tried to relate K_z to the environmental conditions, but considerable work remains to be done on this intriguing problem. Kullenberg (32), using the results of sub-surface tracer experiments in the depth range 5-30 m in coastal waters and open sea regions, proposed a relation of the form

$$K_z = c_1 \frac{\overline{W_a^2}}{\overline{N^2}} \left| \frac{\overline{dq}}{dz} \right|, \quad W_a \geq 5 \text{ m/sec} \qquad (11)$$

where $c_1 = \frac{\rho_a}{\overline{\rho}} \cdot c_d \cdot Rf$ and is in the range $(6\text{-}25).10^{-8}$. The experimental value is $\sim 10^{-7}$.

For shear-generated turbulence the following relation holds (3; 32)

$$K_z N^2 = Rf \frac{\tau}{\rho} \frac{dq}{dz} \qquad (12)$$

The stress τ is

$$\tau = - \bar{\rho} \left(\overline{u'w'} + \overline{v'w'} \right)$$

and we can assume that $\overline{u'w'} \propto \overline{u'^2}$ and $\overline{v'w'} \propto \overline{v'^2}$, which assumption has been used by many authors (e.g. 70). It implies that

$$K_z \overline{N^2} \propto \overline{q'^2} \left| \frac{\overline{dq}}{dz} \right| \quad ; \quad \overline{q'^2} = \overline{u'^2} + \overline{v'^2}.$$

In order to verify this relation the fluctuating kinetic energy must be determined. This is difficult, and requires long time-series of current measurements. Relation (12) is equivalent to

$$K_z = Rf \, \varepsilon \, N^{-2} \qquad (13)$$

using the expression

$$\varepsilon = \frac{\tau}{\rho} \left(\frac{dq}{dz} \right) .$$

Ozmidov (51) used equation 13 to determine K_z for a range of stratifications and energy dissipations, putting $Rf \approx 0.1$. Usually ε is found in the range 10^{-3}-10^{-5} cm^2 sec^{-3}. In the wave breaking zone Stewart and Grant (61) found a dissipation in the range 0.05 - 0.01 cm^2 sec^{-3}.

It is quite clear that the vertical mixing varies considerably depending upon the conditions. It is, therefore, meaningless to intercompare observations of the vertical transport without giving due regard to the environmental conditions.

3.6 Conclusions

Our knowledge about the dispersion and its dependence upon the environmental factors is most advanced by far for the surface layer. It can be summarised that the wind, the current shear, and the stratification are the most important parameters; that the motion is predominantly turbulent, and that the dispersion is a function of the horizontal scale. The thickness of the wind-mixed or wind-influenced layer depends upon the latitude and varies considerably over the year. In many areas it is shallow, much less than 50 m, being shallowest during the warm season.

4. The Pycnocline Layer

Permanent pycnoclines occur in many coastal areas, and in temperate latitudes seasonal thermoclines are developed during the warm season. The formation of these is linked to the influence of the local wind, as described above. The wind-induced erosion of pycnoclines is essentially a one-way transport whereby water from the pycnocline layer is entrained in the surface layer.

4.1 Buoyancy effects

In the pycnocline layer the buoyancy forces dominate the motion, suppressing the vertical exchange through the layer very markedly. Since only a small fraction of the total turbulent energy seems in general to be contained in the vertical fluctuations, the value of Rf_c is small. A representative value appears to be 0.1 (15; 34; 60), even though higher values have been suggested in some cases. For instance, the Munk and Anderson (39) relation gives the value 0.5. The value of the gradient Richardson number Ri is mostly used as a criterion for the possible occurrence of turbulence. The value 1/4 has been determined theoretically (e.g. 36) as the critical value of Ri. When $Ri < 1/4$ in the whole water column, turbulence can develop. Experimental investigations suggest that the critical value of Ri falls in the range 0.1-0.3 (e.g. 67). In the pycnocline layer the overall Ri is usually greater than one, a common range is 1-20, implying a marked decrease of the vertical exchange. Vertical mixing coefficients in such layers in fjords, coastal waters and open shelf seas tend to fall within the range 0.5-0.01 $cm^2\ sec^{-1}$, (18, 26, 34, 46). For the oceanic main-thermocline layer, Rooth and Ostlund (58) found a value of 0.20 $cm^2\ sec^{-1}$ by studying the penetration of tritium from nuclear weapon testing.

Despite this low vertical exchange, the vertical shear effect is also important in pycnocline layers as a dispersion mechanism. This is the case because the current shear is often considerably enhanced in these layers. This compensates for the decrease of K_z since the shear is squared in expressions for the horizontal variances.

4.2 Entrainment

In many cases we have a well-mixed upper layer separated from a lower layer by a sharp pycnocline layer. In the upper layer the fully developed turbulence is maintained by the energy input from a persistent wind, whereas the turbulence in the lower layer is much weaker than in the upper layer. The mixing across the pycnocline layer is then driven by the turbulence in the upper layer and is essentially a one-way transport upwards. This is called entrainment. This causes a gradual deepening of the pycnocline, given by the entrainment velocity, u_e. Laboratory (27) as well as field studies (78) indicate that the entrainment velocity can be expressed as

$$u_e = \text{const} \cdot u_* \cdot Ri_*^{-1}$$

where

$$Ri_* = \frac{g \frac{\Delta\rho}{\rho_o} D}{u_*^2}$$

Here $\Delta\rho$ is the total density difference between the upper and lower layers, respectively, and D is the thickness of the upper layer.

4.3 Small-scale structure

The pycnocline surface is irregular because of the processes active in the layer. The internal wave motion is important and turbulent motion tends to occur intermittently (23, 42, 43). Besides the wind-induced erosion, important turbulence generating mechanisms are shear instability and breaking internal waves. These processes, combined with advection and the very weak overall vertical mixing, tend to give the pycnocline layer a step-wise structure. Relatively thin sheets, of the order of decimetres in thickness, with marked gradients, are separated by thicker, almost homogeneous regions, of the order of metres in thickness. Refined observational techniques are able to resolve these features of the salinity and temperature distribution, but the corresponding small-scale current structure has not yet been satisfactorily resolved. This is an important task, and until it has been solved no clear understanding of the mixing processes can be obtained. Even though small-scale and micro-scale structures in pycnocline layers and deep waters have been detected in many areas of the sea, their generation mechanisms are not yet fully understood. The factors mentioned above seem to be important (24, 74). It is quite clear that the type of structures described influence the dispersion very much, since the distribution of a passive contaminant will tend to follow the natural layered distributions of salinity and temperature. Fig. 3 shows some examples of simultaneous tracer and temperature profiles obtained by the author in different regions. Such internal layers can survive for several days after a dye injection of only a few kilogrammes.

It has been suggested that molecular, so-called double-diffusive processes, are active in the generation of the micro-structure in the sea (see e.g. 67 for a review). These processes are due to the difference in molecular transport coefficients of substances forming a stably stratified system with opposing gradients: for example, warm, salt water on top of cold, fresh water or cold, fresh water on top of warm, salt water. The double-diffusive processes will generate a penetrative convection of salt and heat even though the system is stably stratified. Certain stability criteria must be fulfilled for the occurrence of the convection, and the possible role of these processes in the sea is not yet resolved. It should be noted that the experiments by Turner (65) show that even in the presence of mechanical stirring, double-diffusion can be active.

5. The Deep Water Layer

Deep water is here regarded simply as the water beneath the pycnocline layer. In many shelf areas the mixing induced by tidal currents and winds (e.g. most of the Irish Sea, the southern North Sea) is so strong that the whole water column is nearly homogeneous all year round. In other areas (e.g. the Baltic, the central North Sea) a deep water zone is present either for the whole year, or during the warm season.

The vertical structure : Except in certain special regions, the deep water is stably stratified. The overall Richardson number is quite large.

In many oceanic regions the water beneath the main thermocline is characterized by a structure similar to the one found in the pycnocline layer. The Richardson numbers defined by the small-scale structure can be considerably less than the overall number, and thus small-scale instabilities may occur.

Dispersion in the deep water : Not much is known about the dispersion in the deep water. The influence of the stable buoyancy field is decisive and the vertical mixing is weak. Relations like eq. 13 may be used to estimate K_z, although the applicability of this relation has not been definitely established. Internal waves are a dominant feature of the motion and possible mixing mechanisms are primarily connected with wave instabilities of various kinds (17, 19, 24, 40, 50, 74). A representative range of vertical mixing coefficients cannot be given; values in the range 0.1-0.01 $cm^2\ sec^{-1}$ are indicated.

Moored recording instruments are now providing us with long time-series of current records also in deep waters. Besides the tidal periods the inertial period is important (e.g. 29, 70). Inertial motions have generation and decay times of the order of a few days. It is important from the point of view of dispersion that significant long-period oscillations are usually not resolved; more observations are needed. Current measurements of this kind can be used to estimate the mixing by means of the Taylor hypothesis (64). The Lagrangian correlation coefficient $R_L(\tau)$ for the current velocities is then transformed into the corresponding Eulerian correlation $R_E(t')$, i.e.

$$R_L(\tau) = R_E(t') \qquad (14)$$

assuming that $\tau = \beta \cdot t'$

The magnitude of β depends upon the characteristics of turbulence. For the ocean one may assume $\beta \approx 1$. This approach should be used with caution. It requires that the turbulent (fluctuating) velocity is less than the mean, and often this is not the case in the sea.

Mean current velocities as well as the tidal velocities in general decrease with depth in the oceanic regions. The energy density of the time-dependent motion and the rate of energy dissipation seem to decrease nearly proportionally to the depth (e.g. 46, 70). Dispersion can be expected to have a similar depth dependence, but the experimental investigations are still too few to allow any definite conclusions as to the deep water dispersion.

6. The Bottom Boundary Layer

Thickness : The thickness of the bottom boundary layer is much less than the surface boundary layer although the same physics are involved. In some oceanic regions the thickness is about 1 m, and in most areas the bottom friction velocities are less than the critical friction velocity for re-suspension of non-cohesive sediments (69, 73).

Observations described by Wimbush and Munk (73) show the currents to be driven by the semi-diurnal tide. They increase rapidly and decrease

slowly. The constant stress layer is of the order of 10 cm, the logarithmic layer of the order of 100 cm and the Ekman layer 500 cm thick. The range of u_* is 0.02 - 0.20 cm . sec^{-1} during a tidal cycle and the drag coefficient is 2×10^{-3}.

Of special interest is the stratification in the boundary layer which unfortunately cannot be definitely determined. The value of the B - V frequency in general decreases exponentially with depth and an extrapolation to 4,000 m gives a value of $N = 5 \cdot 10^{-4}$ rads $\cdot$ sec^{-1}. In several areas of the ocean an increased turbidity (particle content) has been observed in the bottom layer (0-100 m) over vast areas. The most recent concentrations reported from these layers (Atlantic ocean) are in the range 100 - 10 $\mu g \cdot l^{-1}$. The highest concentrations are found in connection with strong bottom currents. The amounts appear to be too small to have any influence on the stratification in the boundary layer.

In shallow waters where tidal currents are strong and/or the wind-induced motion reaches the bottom, the boundary layer is of great importance. Observations (e.g. 4) suggest a drag coefficient of about $(2\text{-}4) \cdot 10^{-3}$. The bottom friction velocity is $u_* = (\tau_b/\rho)^{\frac{1}{2}}$ and in the constant layer, which can be several metres thick, the eddy viscosity $A_b = \kappa u_* z$, where z is the height above the bottom. In the same layer the rate of energy dissipation per unit mass can be estimated as $\varepsilon = u_*^3/\kappa z$.

Current measurements in the bottom boundary layer beneath the Florida current gave an average value of $u_* \sim 0.3\text{-}0.4$ cm $\cdot$ sec^{-1}, with peak values about 1.0 cm $\cdot$ sec^{-1} (69). These occurred when the mean and the tidal currents reinforced each other. A critical value of u_* for transporting fine sand at the bottom is $\simeq$ 1.5 cm $\cdot$ sec^{-1} which thus could be reached occasionally beneath the Florida current. It appears that in general the friction velocities are too low to cause re-suspension of sediments. It seems likely that re-suspension occurs on special locations where high current velocities are prevailing. The dominating low-friction velocities and bottom stresses suggest that the dispersion efficiency is low and the boundary layer thin. Low vertical diffusivities are expected.

Interesting attempts to study the bottom nepheloid layers, using combined observations of conductivity, temperature and light scattering vs. depth, are carried out in connection with the Geosecs programme. Preliminary estimates of the vertical diffusion coefficients from these observations infer values in the range 1 - 5 $cm^2 \cdot sec^{-1}$.

Transport along the bottom : In many shallow-water areas high velocities at the bottom lead to re-suspension of deposited material. The stratification of the water column, the tidal currents and wind action are decisive physical factors. In addition the bottom conditions and the type of sediments are important factors. Thus, re-suspension will occur in some areas all the year round during strong tidal currents, but in other areas, where the tides are weaker, re-suspension will only occur on a seasonal basis when stratification is weak and the wind-induced currents can penetrate to the bottom. It should be noted that available observations suggest that the turbulence generated by bottom friction only influences near-bottom layers.

When bottom erosion occurs the concentration profile of suspended matter in the constant stress layer is expected to be of the form

$$C - C_1 = \frac{F \cdot Pr}{\kappa \cdot u_*} \ln \frac{z}{z_1} \qquad (15)$$

where C_1 is the concentration at the level z_1. The flux of particles is F and $Pr = K_z/A_b$ is the turbulent Prandtl number. When the net flux is zero the following profile is expected

$$\ln \frac{C}{C_1} = - \frac{w \cdot Pr}{\kappa \cdot u_*} \ln \frac{z}{z_1} \qquad (16)$$

where w is the settling velocity. Thus, by observing the near-bottom profiles of suspended matter, information about the conditions can be obtained.

Finally, the feature of compensating bottom currents in shallow waters should be mentioned. Their ability to transport material deposited at a distance from the coast back to the coast has been amply demonstrated in estuaries, river mouths, and along relatively shallow-water coastlines where wind-induced upwelling is a regular feature.

7. The Lateral Boundary Layer

In addition to these vertically defined regions of the sea, the horizontally defined lateral boundary layer between the land and the sea is of primary interest. In this layer, with an overall width of about 10 km, a number of transport and mixing processes occur which involve interactions among environmental factors.

Large-scale events, where the rotation of the earth plays a role, are generated by atmospheric forcing. Strong, jet-like coastal currents of baroclinic and essentially transient nature are generated and are important for the renewal of the coastal water mass (e.g. 13). In stratified waters, internal Kelvin waves, i.e. waves with no transverse velocity, of tidal origin and often trapped along the coastline are notable features (e.g. 38). Coastal upwelling, generated by a persistent wind forcing the surface water from the coast, gives rise to a compensating inflow at sub-surface levels. This circulation pattern can effect the return to the coast of material disposed at sea, especially when combined with a certain amount of vertical mixing at sea (e.g. 41).

Special transport phenomena are generated by the adjustment of a stratified field, with quasi-horizontal isolines in the interior of the sea, to sloping lateral walls. Since there can be no salt flux through the wall the isolines must curve to meet the inclined wall at right angles. As a consequence the hydrostatic pressure at a point on the inclined wall is less than at the same depth in the interior. The fluid near the wall will tend to move upwards along the wall until the frictional forces balance the

hydrostatic pressure deficit (55). A transport is thus induced. The importance of this transport has not yet been clarified, but since mixing in the interior of the sea is in general very weak, the lateral boundary mixing may be significant (40, 75). On-going investigations of the lateral boundary layer in enclosed seas like the Baltic, where the internal vertical mixing is extremely weak owing to the permanent pycnocline, will provide valuable information. The effects of the processes in the lateral boundary layer must be recognized in connection with coastal waste disposal.

The near-shore zone : Dispersion along beaches is primarily governed by the wave conditions and to a lesser extent by currents, those generated by meteorological forcing or tides, for example. The nearshore region is sub-divided into swash, surf or breaker, and offshore zones. The former covers the area where the residual wave motion consists of surges up and down the beach face. The surf zone is the area where the wave energy dissipation essentially takes place. The latter zone extends from the breaker line to the depth at which frequent disturbance of bed sediment by wave motion occurs. In relation to this division it is pertinent to consider three aspects of the nearshore dispersion (81) :

(i) Process occurring seaward of the breaker line (in the offshore zone). In this region the mixing induced by agents other than waves will normally dominate.

(ii) In the surf zone the breaking waves generate strong vertical and horizontal mixing. The transport across the breaker line is considerably more effective than the longshore transport.

(iii) The dispersion due to the nearshore circulation cell, covering the width of the surf and swash zones, and consisting of longshore flow with seaward flow concentrated in rip currents. On a plane beach the spacing between the rip currents is of the order of four times the width of the surf zone. This water and suspended matter are transported into the surf zone by the breaking waves, carried alongshore and returned by the rip currents. These are very strong, of the order of 100 cm sec^{-1} up to 300 m or more from the shore, and consequently have considerable transporting and eroding capacity.

The important aspect of this picture is the limiting of effective dispersion to the surf zone. This is in part due to the less intense turbulence outside the breaker line, but mainly due to the transport (pumping) of offshore water through the breaker line into the nearshore circulation cell. The longshore mixing is less intense than the mixing in the breaker zone, and the material is mainly transported with the longshore current, spreading along the beach. Very little spreading occurs upstream of the current. However, the direction of the current is influenced by the direction of the incoming waves.

We may estimate the volume in which the released material becomes diluted over a period of several hours. The height (depth) of the surf is H_b, the width of the nearshore circulation cell is B_b and the length of the

cell (i.e. spacing between rip currents) is L_b. The observations on straight beaches suggest that.

$L_b \approx 4\ B_b$ and $B_b \approx (10 - 100)H_b$

with 0.2 m $\leq H_b \leq$ 2 m. Thus we have the volume $V \approx H_b \cdot 4 \cdot 50 \cdot 50H_b \cdot H_b$. With $H_b \approx 1$ m the volume is 10^4 m^3.

Observations suggest that the longshore transport of sand is directly proportional to the longshore component of wave power, independently of the grain size. This indicates that the bed load transport is important. It also appears that the finer grain sizes are transported offshore more effectively than coarser grains for the same wave conditions.

Theoretical models for predicting the longshore currents and sediment transport depending upon wave conditions and other parameters are available, but the verification of these models is unsatisfactory, owing to lack of reliable data.

On-offshore transport in the breaker zone occurs as both suspended and bed load. Outside this zone, in the offshore zone, the sediment transport is mainly bed load, the energy dissipation being caused mainly by bottom friction.

Different kinds of waves have different transporting properties. Generally, short, steep waves generated by onshore winds have a stronger tendency to carry material offshore than onshore (so-called destructive waves). Longer waves on the other hand (swell) generated by distant storms tend to carry material towards the beach (constructive waves). The nature of the wave, its size, the profile, and the composition of the beach all influence the action of the wave on the beach.

Normally the waves approach the beach obliquely which results in coastal drifting, i.e. longshore transport of material along the bed. This process can act as a sorting agency separating different grain sizes. It would lead too far to discuss all these processes in detail. Clearly they should be considered in each separate case.

For depths exceeding a few metres the information available on transport by wave action of suspended sediments is limited. Obwervations show that surges with velocities above 30 cm sec^{-1} cause temporary suspension of sand grains.

8. Remarks on Buoyant Pollutants

Internal layers of contaminants are often created as a result of submerged injections. The sewage will rise to the appropriate density level and spread out horizontally. In many cases the contaminant is deliberately trapped in a thermocline layer. The mixing in such layers is weak. The possibility of double diffusive convection penetrating the thermocline, with contamination of the surface waters as a result, cannot be ruled out. Since

the density of the affluent, as well as the density stratification of the water, are time-varying factors, it is conceivable that several contaminated layers will form. These are spread out in a fan-shaped pattern owing to the time-dependence of the vertical current structure. The vertical concentration distribution will show large variability.

Contaminated particulate matter is added to the surface layers by dumping, by atmospheric fall out, by adsorption of materials to plankton. Generally these particles will sink, but the sinking and sedimentation rates depend upon the size range of the particles as well as on the turbulence level and the stratification in the water. When mud containing lumps of solid material is dumped, an approximately exponential increase with depth of the concentration in suspension can be expected down to a certain level. The water containing suspended matter will sink to an appropriate level. Various possibilities of predicting the distribution were discussed by Kullenberg (77). Again sharp, rather thin layers of contaminated water will spread out in a way determined by the current structure. In a stable stratification, particulate matter may become trapped in strong density gradients. In pycnocline layers the degradation of trapped particles may lead to increased concentrations of different substances in the water in that layer.

9. Observations of Environmental Factors

With the above discussion in mind it is pertinent to consider briefly the type of environmental observation that should be made to assess the capacity of a given area as a recipient. First it is necessary to plan the field observations carefully. For this purpose one should search for existing information and observations; e.g., from various local authorities and fishermen. It should be borne in mind that, very often, substantial insight can be gained through fairly limited observations. It is not necessarily a good idea to adhere to a very comprehensive and general observational programme. Rather, the field studies should be tailored to the area in question, the purpose and the needs. Here follow some suggestions:

The vertical distributions of salinity, temperature and current should be observed over periods long enough to permit the determination of characteristic oscillations and variations; i.e., the spectral distributions. It is desirable to obtain some knowledge of the residual or drift currents in the area, but it is at least equally important to determine the large-period fluctuations. These are not only semi-diurnal and diurnal tides, and inertial motions, but also other meteorologically induced motions with larger time scales. Furthermore, this should be done on a seasonal basis, since winter and summer conditions are often very different.

The thickness of the more or less well-mixed surface layer and its variations over the year should be observed. Clearly this is a relevant parameter which, together with information about the current, directly gives a guideline as to the capacity of the region.

In stratified waters the vertical resolution of the observations should preferably be such that a multi-layered structure can be resolved. It is

difficult to investigate the relative roles of internal wave motion and of turbulent motion. In an internal wave field the fluctuating kinetic energy can be expected to be proportional to the Brunt-Väisälä frequency (54, 70). The fluctuating kinetic energy can be estimated by means of long time-series of current measurements.

In connection with current measurements, the problem of the relation between Eulerian and Lagrangian fields should be noted. Longuet-Higgins (35) showed that there is a difference between the mean (Eulerian) velocity at a point and the mean mass-transport past the point in a time-dependent current field. This difference, which is due to the Stokes velocity, can be appreciable in areas where the residual velocity is low and the currents mainly have a tidal or inertial character. It may be possible to resolve this by using observations from tri-partite current-meter stations.

The meteorological conditions in the area must also be observed, primarily the wind spectrum. The wave conditions are also of great importance, but more difficult to observe on a long time basis.

It is usually possible to have recourse to some kind of tracer experiments to obtain piece-wise information on the dispersion in an area. Such experiments cannot, however, cover more than a few different conditions, and in order to be of any general value they must be combined with simultaneous environmental observations. Otherwise the interpretation is extremely difficult and can easily yield misleading conclusions.

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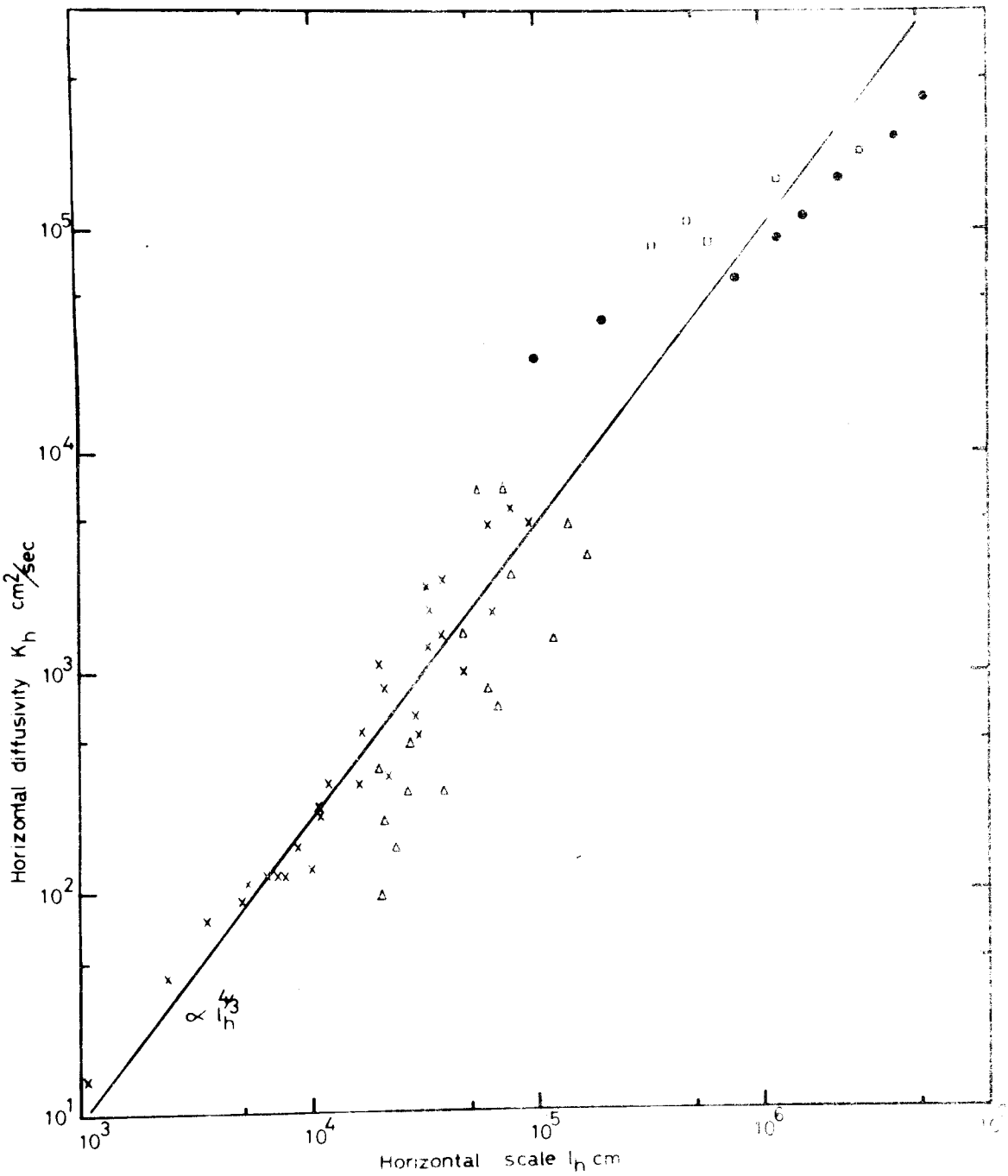

Fig. 1 Horizontal diffusivity K_h vs. length scale l_h.

Symbols : x coastal water, sub-surface layers

Δ sub-surface layers, Lake Ontario

● central North Sea, mixed layer

□ southern North Sea

For data references and treatment see 34.

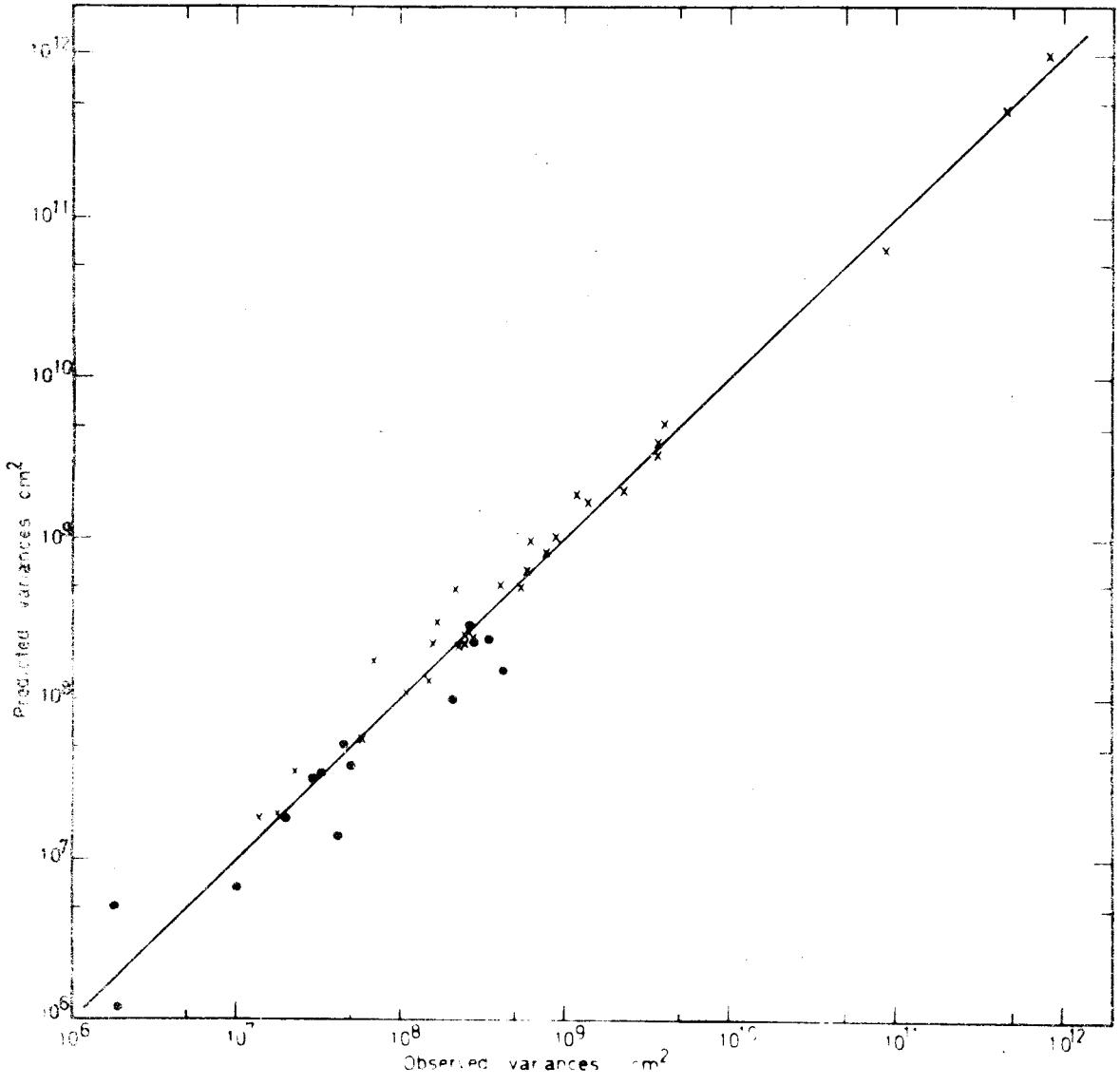

Fig. 2 Predicted vs. observed horizontal variances.
x, longitudinal variance and ●, lateral variance.

For data references and treatment see 34.

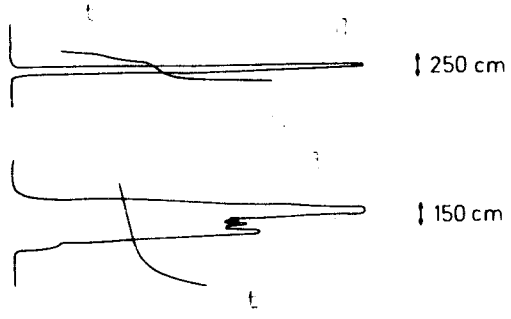

Fig. 3b Vertical profiles of temperature (t) and dye concentrations (d) obtained in calm conditions in the Western Mediterranean about 28 m below the surface.

top : after 1.9 hours of tracing.

bottom : after 1.8 hours of tracing.

Note : depth increases upwards, temperature decreases towards the left.

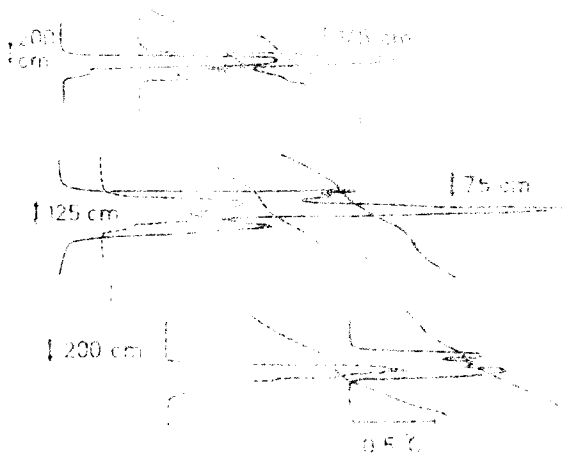

Fig. 38 Vertical profiles of temperature (°C) and [illegible] obtained in calm condition in central [illegible] after 10 hours of [illegible]

(a) [illegible] after 2 hours of [illegible] after 9 hours of [illegible]

(b) [illegible] after 2 hours of [illegible] after 2 hours of [illegible]

(c) [illegible] after 15 hours of [illegible]

[illegible] towards the left.

HEALTH ASPECTS OF COASTAL WATER POLLUTION

by E.W. Mood

CONTENTS

1. Introduction

In almost all areas of the world, pollution of the coastal waters is a serious and rapidly increasing hazard to health of people who either reside or are on holiday in coastal areas. It is a condition which has, or will have, a major impact on the social well-being of inhabitants of the nations located in the Caribbean and adjacent regions. It is a condition which, if allowed to go unabated, may have a serious economic effect upon the economy of an area, particularly that part of the economy that is either directly or indirectly related to tourism.

Pollution of coastal waters is of concern to public health for a number of reasons. There is ample evidence that the consumption of shellfish and fin-fish from polluted coastal waters is a cause of death, disease and/or disability. There is a risk of enteric infection from swimming in waters that receive untreated or inadequately treated sewage. Also, enteric infections among non-swimmers is possible if the beach environment is fouled with faecal material in such a way that the infectious substance is exposed to rodents and arthropods that may be vectors of human disease.

The health of people may be affected adversely by pollution of coastal waters in another manner. Asethetics and mental well-being are related closely to physical health. A fouled marine environment may be unaesthetic, and as such may be a deterrent to a feeling of well-being among persons who are in the vicinity, particularly those who are there on holiday.

2. Contamination of Seafood

2.1 Infections and intoxications from molluscan shellfish

Numerous outbreaks of bacterial and viral infections have been traced to the consumption of raw or partially cooked molluscan shellfish, i.e. clams, oysters and mussels, which have been taken from polluted coastal waters. Shellfish, being filter-feeders, have the ability to concentrate within their systems the microbial life, certain toxic substances and various radionuclides that may be in the water in which these shellfish grow. This concentrating process facilitates the ingestion of a toxic substance or infective organism.

Outbreaks of typhoid fever, paratyphoid fever and infectious hepatitis are but a few of the diseases that have been caused by the consumption of raw or partially cooked oysters, clams and mussels that have been harvested from coastal waters into which raw or inadequately treated sewage has been discharged.

One of the most widespread and famous epidemics of typhoid fever due to the consumption of raw oysters, which were harvested from sewage-polluted waters, occurred in the United States during the late fall and early winter months of 1924 and 1925 (Lumsden *et al.*, 1925). This outbreak had a widespread geographic distribution, with most cases occurring in New York City, Chicago and Washington, D.C. It is impossible to state the exact number of

cases involved in this epidemic, but it was conservatively estimated that there were over 1,500 cases and more than 50 deaths.

The publicity following the recognition that these cases (and deaths) of typhoid fever were caused by the consumption of raw oysters is reported to have caused a marked reduction in the sales of oysters in the U.S., with a concomitant financial loss of great magnitude to the oyster industry in the USA.

Outbreaks of viral infectious hepatitis following the consumption of clams and oysters taken from grossly polluted coastal waters have occurred in several areas of Europe and parts of North America (Mason and McLean, 1962). While it has not been conclusively proved that the consumption of raw clams and oysters from sewage-contaminated waters was the source of these outbreaks, because the causative agent was not isolated in these outbreaks, there is a strong epidemiological association between the consumption of these molluscan shellfish from sewage-polluted waters and cases of viral infectious hepatitis. To date, scientists have been unable to culture the virus of hepatitis under laboratory conditions. If and when such laboratory culture methods are developed, most epidemiologists believe that a cause-and-effect relationship between the consumption of raw clams and oysters from sewage-polluted waters and viral infectious hepatitis will be demonstrated.

Paralytic shellfish poisoning following the consumption of raw clams and mussels has been reported frequently in literature from North America, Europe, Africa and Asia. These molluscs may become toxic to man as the result of the accumulation of toxin derived from several dinoflagellates, of which Gymnodinium brevis, Gonyaulax catanella and Gonyaulax tamarensis seem to be of major importance. The cause of the rapid growth of these dinoflagellates in coastal waters is unknown, but many scientists believe that the discharge of large volumes of wastes into coastal waters may create favourable nutritional conditions for these plankton.

2.2 Fish-borne infections and intoxications

According to the findings of a recent WHO Expert Committee, in most countries where statistical data are available bacterial infections constitute the largest proportion of fish- and shellfish-borne diseases (WHO, 1974). These infections are due either to the direct contamination of the edible portion of the fish or shellfish with pollutants from the waters in which they are grown, or to secondary contamination during landing, processing, storage, distribution or preparation for consumption. There is very little evidence that conclusively links fish-borne infections to pollution of coastal waters. Some of the micro-organisms capable of causing human disease following the consumption of raw fish are normal inhabitants of the marine environment; for example, Vibrio parahaemolyticus, the causative agent of over 50% of all food-borne diseases in Japan, is found in marine waters and bottom sediments in unpolluted waters as well as polluted waters.

The syndrome of methyl-mercury poisoning, sometimes called "Minamata disease", caused by the consumption of contaminated fish and shellfish, is an example of serious health hazard stemming from pollution of coastal waters.

The clinical picture of this disease was first observed in 1953 (Nelson, 1971). However, two outbreaks in Japan in 1970, one in Minamata where there were 121 cases and 46 deaths, and one in the riverside villages of the Agano river in Niigata, where there were 47 cases and 6 deaths, caused this health problem to be recognized internationally as a major consequence of pollution of coastal waters.

Methyl-mercury poisoning in man is an end-product of a complex interplay of biological, chemical and biochemical processes resulting from the discharge into water of metallic mercury, inorganic mercury salts or organo-mercury compounds. The methylation of mercury occurs in the sediments of the bodies of water into which the mercury-containing pollutants are discharged. Once transformed into methyl-mercury, this compound is readily assimilated and concentrated in the flesh of fish inhabiting the polluted waters. When these contaminated fish are ingested by man in large quantities, methyl-mercury poisoning may result. The slow rate of elimination of methyl-mercury in both fish and man potentiates the accumulation of the chemical to toxic levels.

Almost all fish contain some mercury, and therefore pollution of coastal waters can not be blamed for the presence of this element in all fish. However, the discharge of pollutants containing high concentrations of elemental mercury and/or mercury compounds is the primary cause of levels of mercury in fish that are considerably in excess of recommended allowable concentrations.

Mercury is not the only metal which, when discharged into coastal waters, may cause human health problems following the concentration of the metal in some form in fish and the subsequent ingestion of the fish by humans. A list of chemicals that may be hazardous to human health because of the possible concentrating processes by edible marine life includes, but is not limited to, the following: antimony, arsenic, barium, beryllium, cadmium, lead, selenium, zinc.

Another group of chemicals which may be pollutants in coastal waters and which are potentially hazardous to human health if concentrated in edible marine life are the toxic organic chemicals. Almost all of these compounds are synthetic and may be found in sewage, industrial wastes and in run-off from inhabited or agricultural lands. This group of chemicals, often called persistent substances because they degrade slowly, includes many classes of substances, such as the following:

i) pesticides

   a) fungicides
   b) herbicides
   c) insecticides

ii) industrial chemicals

   a) chlorinated hydrocarbons
   b) other halogenated hydrocarbons

of considerable importance to human health is the fact that some of these compounds are capable of being concentrated in certain marine organisms without apparently causing them adverse effects, and that continued consumption of the contaminated marine organisms by humans may give rise to chronic or long term toxicity. To date, only limited knowledge exists concerning the long term effect of most of these compounds upon human health.

One of the toxic organic chemicals that has been found as a widespread contaminant in marine ecosystems is polychlorinated biphenyl (PCB). This compound has been found in edible marine organisms at relatively high concentrations. It has carcinogenic properties which make it particularly hazardous to human health.

Other contaminants of seafood

Oil is a coastal water pollutant which is tending to become more common and more serious in virtually every nation of the world. While its presence in fish and shellfish does not give rise to human intoxication, concentrations which are sub-lethal to edible marine organisms may render seafood that it becomes useless as a source of food. This result may deny many economically deprived persons of a needed source of nutrition. It has been demonstrated that oil in the tissues of shellfish may persist for several months after an oil spill.

Infections from Bathing in Polluted Coastal Waters

General

The discharge of untreated or inadequately treated sewage into the marine environment has several potentially adverse consequences, one of which is the causation of human infections. The increasing numbers and volume of sewage discharges in many of the areas of the world have resulted in intensifying the occurrence of pathogens and increasing their persistence in the coastal waters in the vicinity of sewage discharges. For example, salmonellae have been and are being isolated with persistent regularity from samples of water collected from sewers, bathing beaches and shellfish areas (Drasar, 1971, Gabelle et al., 1974). This group of bacteria has been associated with usage from coastal and estuarine waters of [illegible] (Schiemann, 1974). Other pathogenic bacteria have been found in coastal waters which receive sewage, e.g. the presence of [illegible] in the harbour waters of Penang, Perak, Malaysia (Chan et al., 1974).

Epidemiological studies

For many years, health officials have been concerned about the [illegible] of the transmission of [illegible] which are [illegible] water, [illegible] pollution. Data on [illegible] which demonstrate [illegible] bathing waters [illegible] evidence to suggest that [illegible]

i.e., the greater the degree of pollution of the bathing water the greater the hazard to the health of the bathers. However, these data are difficult to interpret accurately as there are many variables in each of these studies which were not measured or monitored and which may have had a degree of influence on the results.

One of the important findings of some of the epidemiological studies, the results of which have been published, is the identification of specific disease hazards from direct contact with intact faecal material, as may occur when bathing and swimming in the vicinity of raw sewage discharges. Among health officials, it is a generally accepted fact that bathing and swimming near the discharge points of raw or inadequately treated sewage is hazardous, and that the risk of infection is great.

Several early epidemiological studies of typhoid fever linked this disease with swimming in sewage-polluted water (Moore, 1954). Among the studies described in the scientific literature are those occurring in the post-World War I era involving bathing in the New York City and the New Haven harbours. More recent studies have linked typhoid fever with swimming in the coastal waters of Australia and Israel.

Since World War II, two major epidemiological studies have been conducted in efforts to gain a more accurate understanding of the relationship of bathing and swimming in water of various degrees of microbiological quality. One of these studies was conducted in the USA and the other in the United Kingdom.

During the years 1948 and 1950, the United States Public Health Service undertook an ambitious series of prospective surveys aimed at assessing the risk of health of swimmers who swam in polluted waters. The findings of this series of studies were summarized and discussed by Stevenson (1953). Three field studies were organized, one during the summer of 1948 which utilized the bathing beaches on Lake Michigan in the vicinity of Chicago; another during the summer of 1949 which involved the bathing areas on the Ohio river at Dayton, Kentucky; and the third study during the summer of 1950 which involved the coastal bathing areas at New Rochelle and Mamaroneck, New York. In all three of these studies the degree of contamination at the more polluted beaches was not excessive.

The principal finding of the three-year study was that there was an appreciably higher overall incidence of illness among swimmers than among non-swimmers. Upon analysis, this finding should not have been unexpected, since water is an abnormal environment for man regardless of its microbial quality. Infections of the eye, ear, nose and throat accounted for more than one-half of the illnesses reported, and gastrointestinal disturbances for about one-fifth.

Between the years 1953 and 1959, the British Public Health Laboratory Service carried out an extensive and intensive bacteriological and epidemiological study of bathing in sewage-contaminated coastal waters (Committee on Bathing Beach Contamination, of the Public Health Laboratory Service, 1959). Only four cases of paratyphoid fever out of a total of over three thousand cases of this disease reported during the years in question

could be related to swimming in polluted water. These four cases were among children who bathed at two grossly polluted beaches.

The results of the analyses of these data caused the committee to conclude that "bathing in sewage-polluted sea water carried only a negligible risk to health, even on beaches that are aesthetically unsatisfactory" and that this risk was probably associated with chance contact with intact aggregates of faecal material that happened to have come from infected persons.

The lack of conclusive evidence concerning the relationship between water quality and the health of bathers does not merit, at this time, a specific conclusion concerning the effect of coastal water pollution on the health of bathers. However, available eipdemiological data suggests that a relationship does exist and that the greater the concentration of raw or inadequately treated sewage in the water, the greater the hazard to the health of the bathers.

4. The Beach Environment

By analysis of epidemiological data and by deductive reasoning, it may be demonstrated that a health hazard exists if beaches become fouled with certain pollutants, especially intact faecal material. Intact faecal material on beaches can spread pathogenic micro-organisms to humans by contact or through the media of arthropods and rodents which may feed on this material. Several studies have traced human disease to contact with faecal material in the beach environment. As will be discussed subsequently, coastal water pollution that is of such scope and magnitude as to cause the beaches to become fouled is very undesirable for aesthetic purposes also.

5. Aesthetics of Water Pollution

Aesthetically pleasing scenes of water and the immediate adjacent areas add to the quality of human experience. The beauty of nature is often best revealed through a visual setting which includes aesthetically pleasing waters and coastal areas. Pollution, if visible in any form, reduces the aesthetic value.

Aesthetically pleasing scenes seem to contribute to good mental health and a feeling of well-being. On the other hand, pollution, if visible, is often depressing and tends to be a deterrent to good mental health and a feeling of well-being. Unfortunately, to date, there is no way to quantify or to assess objectively the actual value of aesthetically pleasing experiences. Therefore, no-one can assess the actual value of a visual scene of clean, clear coastal waters that is interpreted by the viewer as aesthetically pleasing.

Recognition, identification and protection of the aesthetic values and qualities of unpolluted coastal waters should be an objective of all coastal water management programmes. When people come to the seaside and the beaches

to relax and enjoy themselves, they need the exhilaration and yet the tranquility of a visual experience which is aesthetically pleasing and which contributes to the promotion of their good mental health and well-being.

6. Temperature as a Water Pollutant

In some places, coastal water is used as a coolant in industrial processes and in the generation of electrical energy. Such practices often result in "hot spots" or spot heating of limited areas of the coastal water in the immediate vicinity of the discharge of the heated water. There is a health hazard associated with this thermal pollution, if the temperature of the water is significantly in excess of 37°C and if a person swims or accidentally becomes immersed in this heated water for a prolonged period.

7. Health Criteria for Coastal Waters

Health criteria for coastal waters are needed in the analysis of coastal water pollution problems and in the development and maintenance of coastal water management programmes. A few basic criteria follow:

i) All coastal waters and the adjoining beaches should be aesthetically pleasing to the eye. The water should be of such quality that it is capable of supporting aquatic life-forms that have aesthetic value.

ii) All coastal waters should be virtually free from:

   a) materials that may settle to form objectionable or undesirable deposits;

   b) floating debris, oil scum, and other similar materials;

   c) substances that may produce objectionable or undesirable colour, taste, and/or turbidity.

iii) Nothing that may produce, support or attract undesirable aquatic or terrestrial life should be discharged into coastal waters.

iv) All coastal waters, particularly those used for recreational activities, should be sufficiently free of pathogenic micro-organisms and toxic substances, so that there is a negligible risk of infection, toxicity or irritation to those who bathe or swim in this body of water.

v) All coastal waters from which fin-fish and/or shellfish may be harvested for human consumption should be sufficiently free of pathogenic micro-organisms and toxic substances, so that edible marine life may be consumed with negligible risk of infection, short-term toxicity and/or long-term toxicity.

vi) No heated water should be discharged into coastal waters so that the temperature of the resulting mixture of water would cause adverse effects to any person who might swim or bathe or accidently might become immersed in the water.

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POLITICAL ASPECTS OF MARINE POLLUTION AND DEVELOPMENT OF POLITICAL AWARENESS OF MARINE POLLUTION PROBLEMS

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CONTENTS

1. Introduction

Current international negotiations at the Third United Nations Conference on the Law of the Sea 1/ (UNCLOS) have thrown into sharp focus the political aspects of marine pollution and underlined the clear need for the development of political awareness in respect of these problems. Problems of pollution do in general require policy decisions at both the national and international levels. Policy decisions are taken by politicians and other decision-makers. Such decisions, if they are to be meaningful and effective, must indeed reflect the scientific and technological realities of marine pollution. The need would therefore arise for decison-makers to be well-informed about the basic facts of pollution. Knowledge of these facts is fundamental to the understanding of the environment and the deleterious effects and consequences that pollution has in the human environment and on the very survival of mankind.

The pollution problem cannot and should not be seen by decision-makers or dealt with by them in vacuo; it is an extremely difficult and complex problem. The land, sea and air form part of a single ecosystem. The seas and oceans, which cover roughly 71% of the earth's surface, constitute an essential part of the biosphere 2/. In view of this elemental fact, decision-makers must take an integrated global approach to the pollution problem. The approach cannot be piecemeal. A piecemeal rather than organic approach will produce temporary solutions and lead to conflict and chaos and eventually to environmental disaster.

An integrated approach to the pollution problem must be predicated on the recognition and awareness that pollution prevention and control are matters of urgent priority that cannot await the slow processes and bureaucratic inertia of national and international decision-making.

In recognizing pollution prevention and control as a problem of increasing urgency, decision-makers need constantly to be aware of the fact that pollution chokes growth and snuffs out in time the very essence of life itself. What is at stake is the destruction of the life-sustaining environment and mankind's survival therewith. This fact cannot be over-dramatized in order to bring the point home. From earliest times, the primary concern has been with protecting man from his environment; today, however, that concern must necessarily shift to protecting the environment from man himself.

1/ The Conference, convoked by the UN General Assembly, has already held five sessions; the first procedural in New York in November 1973 and four substantive sessions held in Caracas (1974), Geneva and New York (1975) and New York (1976). Next Session scheduled for New York (May 1977). Negotiations at the Conference take place in closed informal sessions without records. Reference therefore to positions taken by states will be made in general terms without pointing specifically to sources.

2/ "Protection of the Marine Environment" from study of National Petroleum Council of USA entitled Ocean Petroleum Resources, March 1975, p.55.

This lecture deals with the political aspects of marine pollution and the development of political awareness of marine pollution problems. In short, it is concerned with the politics of pollution. It can be divided into two main parts:

i) political aspects of pollution, and

ii) development of political awareness of marine pollution problems.

Pollution politics raise many complex and sensitive issues. I cannot deal with them all in the course of a short lecture, which is intended merely to agitate some of the issues and to provoke discussion thereon. I have chosen the current UN Law of the Sea Conference as the most convenient forum for seeing the politics of pollution at work.

As stated earlier, the decision-maker must have at his disposal the basic facts on pollution which are fundamental to the process of decision-taking. It is the duty of the political scientist to translate the technological and scientific data on pollution into language clear enough for the decision-maker to understand and appreciate its purport and significance. These data and information form necessary inputs into the decision-making process.

2. Political Aspects

2.1 Decision-making inputs

Knowledge and information about marine pollution based on continuing marine scientific research and environmental monitoring must be fed into the decision-making process so as to enable policy makers to get a clear perception of the facts, to take stock of, and evaluate, their options in the light of their national interest, with a view to taking effective decisions for the preservation of the marine environment. Marine scientific research programmes are vital for obtaining the necessary information and knowledge. The public must be made aware of this so that they can demand the establishment of national scientific research organizations and ensure national support for international bodies like IMCO, IOC, FAO, WMO and WHO, which are engaged in the task of combatting pollution.

The debates and discussions on the marine pollution question at the marathon Law of the Sea Conference have revealed the availability to the participants of much basic data on the problem. It is clear to all that man is the polluter. He is the aggressor as far as pollution is concerned. The environment is his victim. The environment does not pollute itself; although natural oil seepages from the seabed have often been made the scapegoat for oil pollution of the sea. It does appear from emerging trends at the Conference that a definition of pollution has been agreed to informally. This definition, which indicts man, reads as follows:

> "Pollution of the marine environment means: the introduction by man, directly or indirectly, of substances or energy into the

marine environment (including estuaries) which results or is likely to result in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of the quality for use of sea water and reduction of amenities." 3/

This definition, which was originally proposed by the Inter-governmental Working Group on Pollution (IWGP) in November 1971, was endorsed by the United Nations Conference on the Human Environment, in Stockholm, Sweden, in 1972. 4/

Marine pollution cannot be contained in water-tight national compartments and boundaries, regardless of whether or not the polluter desires so to contain it. It does not respect any fine political or legal distinctions between national sovereignties and jurisdictions. The realization of this fundamental fact points to the need for international solutions.

It is to be noted that all pollutants end up in the seas and oceans around us. These pollutants come from, or through, the atmosphere and from land-based sources. They consist of toxic wastes, garbage and sewage, industrial wastes and effluents, and innumerable substances like non-rust aluninium parts, inorganic plastics, oil and oily wastes, nuclear fall-out and radioactive wastes.

Marine pollution comes from many sources, including land-based activities, vessels and underwater vehicles of all types and sizes, off-shore terminal activities and related storage and transportation facilities, exploration and exploitation of the resources of the seabed, and marine scientific research of the seabed.

Man has used the seas and oceans as his "dust bin" or "garbage can". He has dumped his wastes there, some of which are toxic and so destructive of marine organisms. Dumping, which is defined by the 1973 IMCO London Convention on the Dumping of Wastes at Sea as an intermittent injection of waste materials into the sea, must be rigidly controlled. Since man depends to a large extent on marine life for his food, irrational dumping can result only in the poisoning and decimation of marine living resources and consequently in serious hazards to human health.

Although the seas and oceans have vast means of self-purification, these powers are by no means infinite. It is true that the natural ecological systems can absorb many of the effluents of human activity and reprocess them into substances that can be used by, or rendered harmless to, other forms of life; but where industrial and other effluents are released

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3/ Art.1, Ch.1 - "Protection and Preservation of the Marine Environment, Revised Single Negotiating Text (RSNT)," Third UNCLOS, UN Doc. A/Conf. 62/WP.8/Rev.1/Part III, 6 May 1976.

4/ See UN Doc. A/CONF 48/14, Annex III.

or dumped into our waterways and oceans on a sufficiently large scale, their natural absorptive mechanisms become saturated. 5/ These wastes can build up and have harmful and hazardous effects on the health of the environment and its aesthetic value.

Pollution grows slowly but it explodes overnight. Hypothetically, it may take five years to reach a level that may not be considered unsafe, but two days later it may reach a dangerously explosive level with tragic irreversible consequences. Pollution is therefore an "exponentially" 6/ increasing quantity in the world's ecological system. It has been concluded that, if pollution continues to grow at its present rate without any serious and concerted global effort to reverse that trend, the length of life of the biosphere as an inhabitable region is to be measured in decades rather than in hundreds of millions of years. 7/ Increasing and reasonably objective evidence has shown that this point needs no dramatization.

2.2 Pollution and economic development

One of the basic political dilemmas facing the current Law of the Sea negotiations is the question of balancing the need to industrialize in the process of economic development with the obligation to protect and preserve the marine environment. The running debate on this question has revealed sharp conflicts of interests between the newly environmentally-oriented developed countries and other countries, particularly a majority of developing countries which realize that pollution is a necessary by-product of the industrialization process, so essential to their economic development.

Participants in the Conference negotiations have at their disposal certain basic data on the pollution problems on which they can take decisions and make choices in the light of their national interest. They all see pollution as a result of man's increasing utilization of energy. Evidence is incontrovertible that the process of economic development is in fact the process of utilizing more energy to increase the productivity and efficiency of human labour. A direct correlation exists between the wealth of a human population and the amount of energy it consumes. A natural corollary flowing from this correlation is that the greater the wealth of a state, the greater its pollution. It is therefore not coincidental that the fifteen most under-developed states in the world (the majority with an annual income per capita of less than US$100 in Africa, Latin America and the Caribbean) utilize the least energy and are probably among the least polluted areas of the globe.

5/ For a discussion of this point, see "The Limits to Growth", A Report for the Club of Rome's Project on the Predicament of Mankind, pp.68-69 (Earth Island Ltd., London, March 1972)

6/ See Ch.1, "Nature of Exponential Growth" id., pp.25-44 for definition of the term "exponential".

7/ See CT. Evelyn Hutchinson's article "The Biosphere" in Scientific American, Sept. 1970, p.215.

On the basis of this evidence, developing countries are arguing persuasively that their "obligation to protect and preserve the marine environment" 8/ must be conditioned on the level of their economic development and their capabilities. What they have said is that developed countries have in their industrialization processes polluted the environment, in some cases beyond repair; it is now the turn of developing countries to pollute in their development process. To deny them the right to pollute at this stage of their development process is to condemn them to eternal under-development. They see themselves as having no means of choice, no choice of means. They have been told that technology which has created pollution has the capacity to solve it. In response, they have drawn attention to the high costs of technology which they cannot afford, and in any case to afford it would be to reduce any corresponding benefits from the industrialization process, leaving them in the same mired state of under-development. They insist that developed countries, which are mainly responsible for the pollution of the marine environment, should bear the costs of eliminating it and provide the technical assistance required for the use of anti-pollution devices and installations in their industrialization process which is a sine qua non for their economic development. It is known that a certain developing country in Latin America has permitted the establishment in its territory of an industry from a developed country in which that industry was prohibited because of the latter's concern with environmental pollution. That developing Latin American state, having costed its options, responded to the dictates of its national interest and saw its economic development as an urgent priority in reducing its chronically high unemployment levels and raising the low standard of living of its peoples. That argument is on its face faultless. It can, however, be carried too far and may lead to absurd conclusions; needless to say, in the case of pollution, to tragic results.

A good example of this can be seen in the debates, informal discussions and consultations of the current Law of the Sea negotiations on standards for land-based industries compared to those for offshore activities, such as the exploration and exploitation of the seabed and ocean floor for oil and the dumping of oil and wastes from every source. Developing countries have argued that standards for land-based industries should be lower than those for offshore activities. They agree to the highest possible standards for offshore activities because most of those activities are at present undertaken by the developed, industrialized countries or their entities, which can afford the high technology costs of anti-pollution devices and equipment. While one may agree that lower standards can be set for some land-based industries which do not produce highly toxic wastes, so as to assist the industrialization process of developing countries, it would be quite absurd, possibly suicidal, to permit lower standards for all land-based industries, some of which produce highly toxic wastes. The international community must not sympathize with this developing country position. It must demand the

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8/ See Arts 2, 3 and 4, RSNT, UN CONF.62/WP.8/Rev.1 Part III op. cit. supra.

highest standards for land-based industries which have highly toxic products and wastes (some chemical industries) and for nuclear and nuclear-powered industries with their ever-increasing possibility of "nuclear" accidents and the production of radioactive wastes, both detrimental to life itself.

Although most developing countries are not in the happy economic position of Canada and cannot therefore speak in the same strong anti-pollution strain as Prime Minister Trudeau, his words to the Canadian House of Commons, when he spoke on the Arctic Pollution Prevention Act of Canada on 24 October, 1969, can bear repetition here:

> "... Canada will not allow what has been described as the expansion of prosperity at the expense of posterity ... the Canadian government will not sacrifice, in the name of progress, a clear and healthy environment to industrial and commercial development ... It will not permit this to happen either in the name of freedom of the seas or in the interests of economic development ..." 9/

No developing, undeveloped or hard-core underdeveloped country can permit "at the expense of posterity" low standards for the establishment of land-based industries which are highly toxic. No country can permit this in reckless disregard for the continuing existence of life itself. The political dilemma continues and must be sensibly resolved if effective international decisions are to be taken in respect of pollution of the marine environment.

2.3 Pollution and innocent passage

In addition to the call by some developing states for lower international standards for land-based industries, a few developing states, with growing merchant navies, have also been insisting on the requirement that developing countries should not have to meet the high international standards laid down for the design, construction and equipment of ships. Some states have threatened not to permit the passage in their territorial waters of ships that do not meet international standards, fearing that such ships will be high-pollution risks. This threat has raised the question of the right of innocent passage for foreign vessels in the territorial waters of a state and the refusal of that right by a state on the grounds that an act of pollution, or the high risk of pollution, breaches the innocence of passage.

The right of innocent passage of foreign vessels in the territorial sea of another state is a well-settled norm of customary international law, which has been codified in Arts. 14 and 17 of the 1958 Geneva Convention on

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9/ See Donat Pharand "Oil Pollution Control in the Canadian Arctic" (Texas Int'l Law Journal, Vol. 7 No.1, Summer 1971, p.61). Also L. LeGault, Canadian Arctic Waters Pollution Prevention Legislation, (Proceedings of 5th Annual Conference of L.O.S. Inst., Rhode Island 1970, p.296).

the Territorial Sea and Contiguous Zone. The passage is innocent as long as it is not "prejudicial to the peace, good order or security of the coastal state". An act of pollution, accidental or wilful, has not been held to prejudice the good order or security of a state; much more so threats of pollution to the territory of the state. Some states, among them Canada, have, however, held that a grave danger or threat to the environment of a state constitutes a threat to its good order and security, and indeed perhaps to its continued existence. They have therefore asserted their sovereign right to take steps, including legislation, to ensure adequate protection of that environment from pollution or artificial deterioration.

Objective criticism of the right of innocent passage has in fact centred on the absence of a clear definition of "innocent". States have differing perceptions of the concept of innocence. It has been argued that since a state is empowered to make and enforce its "sanitary" regulations in its territorial sea and in a zone contiguous to it, it can make and enforce pollution prevention and control laws under these regulations. The term "sanitary" is considered broad enough for this purpose. There is some consensus at the current Law of the Sea negotiations that pollution prevention and control is one of coastal states' interests which must be observed by vessels in the course of their innocent passage through territorial waters. Failure of a vessel to abide by regulations proclaimed by the coastal state in this regard can be viewed as prejudicing the peace, good order and security of the state. It is a considered view that a ship which does not comply with anti-pollution regulations of the coastal state can be denied access to its coastal waters.

What has been said above is an interpretation of existing provisions in the 1958 Geneva Convention on the Territorial Sea. No explicit provision exists to deny the right of innocent passage to a foreign ship on the grounds of an act of accidental or wilful pollution or a grave potential threat thereof. Delegations at the Law of the Sea Conference are, however, seeking to close that loophole, if indeed any such loophole existed. They have proposed for a new law of the sea convention an article 10/ which seeks to define twelve activities engaged in by a vessel which will make its passage non-innocent. One of those activities listed is "any act of wilful pollution". 11/ The inclusion of "wilful" before "pollution" represents a compromise in the informal consultations in view of the strong criticism of the original proposal by shipping interests, some major maritime powers and some flag-states of convenience. What may appear ironic is that it was some major oil-producing developing countries (growing oil-tanker powers themselves since the oil crisis) that led the battle in defence of the marine environment and in the designation of an act of pollution as a breach of the right of innocent passage. In the course of informal discussions on the question, some states have suggested that the passage of vessels such as

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10/ See Art. 16(2) (a) to (l) RSNT, A/CONF.62/WP.8/Rev.1, Part II, 6 May 1976.

11/ See Art.16 (2) (h) id.

super-tankers and liquified natural gas carriers (LNG vessels) is a potential pollution "threat" to the marine environment, and, as such, those vessels require the prior consent of the coastal state before they can enter its territorial waters. It is the fear of such an arbitrary, subjective interpretation of "innocent" in the concept of innocent passage that has caused a fairly large number of states, both developing and developed, to oppose the inclusion of pollution as one of the activities that would render a ship's passage not innocent. These states, whether oil producers or oil refiners, have a vital interest in the movement of tankers. Environmentalists appear to be quite unhappy at the inclusion of "wilful" before pollution inasmuch as its application to activities narrows the present regime; that is, if it is agreed that under the existing regime a coastal state has broad jurisdiction over pollution offences or even over the risk of such offences. 12/

Another point of controversy is a provision that precludes the coastal state from regulating the design, construction, manning or equipment of foreign ships. The provision reads as follows:

> "Such laws and regulations (laws made by the coastal state in its territorial sea) shall not apply to or affect the design, construction, manning or equipment of foreign ships or matters regulated by generally accepted international rules unless specially authorized by such rules" 13/

Some states consider that in the absence of so-called "generally agreed international" rules, coastal states should be permitted to make rules regarding the design, construction or equipment (if not manning) of foreign ships that enter their territorial sea. They say they cannot afford the potential pollution risk of sub-standard ships registered in flags-of-convenience states, some of which are "straw-states" from which compensation for damages may never be recovered. Serious questions have been raised about the term "generally agreed international rules" in view of the fact that these rules, fragmentary as they are, tend to be set by IMCO Conferences dominated by major maritime states, and particularly when such rules are embodied in conventions ratified by few states. A compromise solution which has been suggested in informal consultations reads as follows:

> "Coastal states, in establishing such laws and regulations, shall not require foreign ships to conform to rules and standards which are higher than those generally accepted internationally in respect of their design, construction and equipment; and to the maximum extent possible shall seek to promote and adopt, as far as practicable, uniformity of such rules and standards."

12/ See Patricia Birnie's monograph on "Vessel Source Pollution: Is there a single negotiable solution" A working paper produced for the fourth session of the Third UNCLOS, March, 1976, p.5 (Sierra Club, N.Y.).

13/ See Art. 20 (2), RSNT, Part II, op.cit. supra.

This compromise still leaves unanswered the question as to the means to reach agreement on "generally accepted international rules and standards". Conference politics do indicate that IMCO is hardly the acceptable forum, unless IMCO itself goes on a membership drive to bring into its fold the other 67 or more states of the international community and ensure their participation at IMCO Conferences, perhaps by paying passages for a certain number of delegates as is done for the regular sessions of the United Nations General Assembly.

2.4 Pollution jurisdiction in the Exclusive Economic Zone (EEZ)

Unlike the territorial sea, which is recognized in customary international law and, with the exception of the right of innocent passage, is considered as part of the territory of the state, the Exclusive Economic Zone (EEZ) is a bold and novel concept. The concept of an EEZ is being proposed for adoption at the Third UN Conference of the Law of the Sea as part of a compromise package of a 12-mile territorial sea and a 200-mile EEZ (measured from the baselines from which the territorial sea is measured). The EEZ will then in effect be 188 miles across. Its main proponents consider it primarily as a zone of economic resource jurisdiction, but also with jurisdiction to protect the coastal state's sovereignty over its resources, living as well as non-living, in the zone. They have considered pollution as a force striking at the very root of their economic resource jurisdiction in that resources, particularly living marine resources, are vulnerable to pollution. Hence to protect their resources, they posit the need to assume pollution jurisdiction in the zone. The article proposed will give the coastal state in its exclusive economic zone "jurisdiction with regard to the preservation of the marine environment, including pollution control and abatement". 14/ The main supporters of the concept of the EEZ, comprising a broad cross-section of the Conference participants, would prefer the inclusion of the word "exclusive" before "jurisdiction" so as to ensure at least a priority of jurisdiction for the coastal state.

As is to be expected, the major maritime states with large shipping interests, oppose the pollution jurisdiction of coastal states in the EEZ, quite apart from fearing what they describe as "creeping jurisdiction". They look on the EEZ as high seas where all states enjoy the freedom of navigation and flag states have jurisdiction and control over vessels flying their flag for all civil and criminal matters including pollution. Ship and cargo-owning states have in practice not assumed effective jurisdiction over their vessels in cases of pollution of a zone like the EEZ which is not part of the territorial sea. Existing marine rules are very lax in this regard. They tend to be much more oriented towards shipping and cargo interests rather than towards the preservation of the marine environment.

The article as worded at present leaves the question of jurisdiction unresolved. It does allow for concurrent jurisdiction with all the attendant

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14/ See Art. 44 (1) (d) RSNT, Part II, op. cit. supra.

confusion that creates. To protect the environment, a proper balance will have to be struck between coastal-state jurisdiction and flag-state jurisdiction on the basis of a set of agreed rules. Strong coastal-state jurisdiction over pollution in the EEZ may, however, be the way to preserve the marine environment in view of the genuine link between the coastal state's resource jurisdiction in the zone and its interest in protecting its resources from the ravages of marine pollution.

2.5 Flag-state jurisdiction

One of the main conflicts to be resolved in respect of pollution by vessels is the question of the jurisdiction of the coastal state vis-à-vis the flag state. As indicated earlier in the discussion of the EEZ, flag states guard jealously their jurisdictions over their vessels. The traditional rule of freedom of the seas has been the dominant concept invoked in relation to jurisdiction over vessels and matters related thereto. A recognition of this freedom does imply minimum national control by states over the seas and oceans, beyond a narrow belt of territorial sea. Following on this concept, flag states have over the years assumed exclusive control over their vessels and have brooked no interference with this control from other states. The interests of the flag state are best served by the free and expeditious movement of its ships. The flag state cannot afford its ships to be tied up in foreign ports by reason of a port state's exercise of jurisdiction over them.

Be that as it may, the question to be answered is whether a flag state has in existing law a universally recognized obligation and duty to prevent pollution from its vessels. Given some IMCO Conventions (ratified by a few states) and the 1972 Stockholm Declaration on the Human Environment (subscribed to by a large number of states, but not binding on any), it does appear that the question can be answered in the affirmative. Many coastal states are of the view that flag-states (and particularly those of convenience) have taken their duty and obligation lightly in respect of pollution prevention from their vessels. Coastal states feel that they have a direct interest in protecting the marine areas under their jurisdiction from pollution by vessels. Needless to say, the corporate international community has also a vested interest in the global protection of the marine environment.

The articles on the question of flag-state jurisdiction 15/ under discussion at the Law of the Sea Conference have come under massive criticism from a majority of states. In their view, the articles in the text, prepared as a negotiating document by the Bulgarian Chairman of Committee III of the Conference (which deals with marine pollution), reflect provisions in a paper (L24) presented on 21 March, 1975, by the United Kingdom on behalf of nine states including some members of the European Community (EEC) and some Eastern European socialist countries. The major weakness of these articles appears to be their imbalance inasmuch as they give too little power to the coastal state and leave too much discretionary power and priority jurisdiction with the flag state to take legal action against their own ships for pollution

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15/ Arts. 26 to 39, RSNT Part III, see UN Doc. A/CONF.62/WP.8/Rev.1/ Part III, 6 May 1976.

damage to the marine environment. As a result, the articles seek to preserve the rules governing the traditional freedom of the sea as it relates to vessels of flag states. Further, the articles are unacceptable in that they adhere to the old principle of conferring sovereign immunity on all military and civilian ships and aircraft operated by the state. In these days of ever-increasing state participation in commercial activities (and in some cases with no clear distinction between commercial and non-commercial activities), a large number of ships would be exempt from pollution liability if a blanket provision for sovereign immunity is accepted by the Conference. It is admitted that an interference with government ships, particularly non-commercial ones, can lead to misunderstandings which may result in hot conflicts. A provision should therefore be included in any new treaty, which would require governments to assume absolute liability for any pollution damage caused by their ships and to make full reparation. Such a provision would avoid the question of a coastal state assuming jurisdiction over foreign-government, non-commercial ships, including war-ships. Once governments have a genuine concern for the environment, reasonableness must be the essence of their approach to the uses of the seas and to the provision of a balanced set of rules to govern jurisdiction conflicts.

2.6 Freedom to pollute and international jurisdiction

It is unfortunate that states have not always been reasonable in their approach to the uses of the seas. They have interpreted the freedom of the high seas to mean a freedom to exploit marine resources beyond national jurisdiction in an irrational and unrestrained fashion. It would appear as if they have stretched the freedom of the seas to include in its ambit a freedom to pollute. Traditionally, states have looked on ocean space beyond national jurisdiction as a free-for-all or up-for-grabs area. They consider it a province for plunder. The United Nations and its specialized agencies have recognized the need to turn man around and away from his collision course with the marine environment. In such a collision, both man and the environment would be critical casualties.

The United Nations has in 1970 decided that the area beyond national jurisdiction (the Area) and its resources are the common heritage of mankind. The area is not a res nullius and no longer up for grabs. The waters are still free for navigation; but there is no freedom to exploit resources or to pollute the marine environment.

Pursuant to the concept of the common heritage, the Third UN Conference on the Law of the Sea is engaged in the exercise of elaborating a constitution for an International Authority (international regime and machinery) to govern the activities in ocean space beyond national jurisdiction. The Chairman of Committee I of the Conference has produced a Single Negotiating Text (Revised) 16/ containing proposals for such a constitution. Of the 63

16/ A Single Negotiating Text, prepared by the Camerounian Chairman of Committee I (International Regime and Machinery) of the Conference, contains the Chairman's perceptions of what he believes may be an emerging consensus of an acceptable constitution for an International Authority. The Text, like the other negotiating texts of the Conference, has no other status than that of serving as a basis for continued negotiation without prejudice to the right of any delegation to move amendments or to introduce any new proposals (UN Doc. A/CONF.WP8/Rev.1 Part III).

articles and four annexes of the Revised Single Negotiating Text under reference, only one Article deals with the protection of the marine environment. That is Article 12, which reads as follows:

> "With respect to activities in the Area, necessary measures shall be taken in order to ensure effective protection for the marine environment from harmful effects which may arise from such activities. To that end the Authority shall adopt appropriate rules, regulations and procedures for inter alia:
>
> (i) the prevention of pollution and contamination, and other hazards to the marine environment, including the coastline, and of interference with the ecological balance of the marine environment, particular attention being paid to the need for protection from the consequences of such activities as drilling, dredging, excavation, disposal of waste, construction and operation or maintenance of installation, pipelines and other devices related to such activities,
>
> (ii) the protection and conservation of the natural resource of the Area and the prevention of damage to the flora and fauna of the marine environment."

This provision is couched in very general terms and is quite imprecise. The "necessary measures" are to be taken, but it is not clear by whom. Is it to be inferred that the "measures" are to be taken by the Authority, since it is the Authority that shall adopt appropriate rules "to that end"? Or is it left deliberately open-ended so as to allow states and the International Authority to take "necessary measures" concurrently? Such open-endedness can lead only to ambiguity which will result in ineffective measures to protect the marine environment.

The Authority will be responsible for, among other things, regulation of the exploration and exploitation of the resources of the sea-bed and ocean floor in international jurisdiction (the Area). Exploration and exploitation in national jurisdictions have caused marine pollution, particularly in cases of oil exploitation. Offshore petroleum operators have often blamed natural oil seepage for pollution of the marine environment when in fact their own operations have largely been responsible. In addition, because of the intense activity of oil tankers in the area and other support ships, pollution from these vessels also takes place. Hence, if in national jurisdictions, pollution from these activities is not effectively regulated, it will be quite naive to believe that states will, in a convention, give the International Authority the power to make effective rules, take necessary measures and enforce them so as to prevent and control pollution and punish offenders, since the Authority will be exercising jurisdiction over ships to the prejudice of the flag state's sovereignty and sacred exercise of the freedom of the sea. Proper concern for the environment does dictate the need to confer comprehensive powers on the Authority to deal with pollution in the Area.

2.7 Liability and responsibility

Responsibility and liability of states and entities have always been complex issues in international relations. They still remain unsettled.

In view of the fact that states have the obligation and duty to protect the marine environment, it should follow then that they be held liable for any damage done to it by themselves or by entities under their control and jurisdiction. The provision on Responsibility and Liability under discussion in the current Law of the Sea negotiations is Art. 44 of the RSNT Part III, 17/ which reads as follows:

"1. States are responsible for the fulfilment of their international obligations concerning the protection and preservation of the environment. They shall be liable in accordance with international law for damage attributable to them resulting from violations of these obligations.

2. States shall ensure that recourse is available in accordance with their legal systems for prompt and adequate compensation or other relief in respect of damage caused by pollution of the marine environment by persons, natural and juridical, under their jurisdiction.

3. States shall co-operate in the development of international law relating to criteria and procedures for the determination of liability, the assessment of damage, the payment of compensation and the settlement of related disputes."

This provision is broad and general in its terms. It appears to cover liability for all activities under the jurisdiction or control of states which cause damage to the marine environment. It does not deal in depth or detail with some of the serious problems regarding liability and compensation for pollution damage. It dismisses the question summarily by stating that liability will be "in accordance with international law". State responsibility and liability are difficult, complex and thorny areas of law, which need to be urgently clarified and codified. What seems to be required is a detailed annex to the Convention of this subject or a separate treaty to be concluded at a Conference with universal representation similar to that of the Third UNCLOS. The provision does not advert at all to the question of degree of liability, whether it should be strict or absolute, to the requirement of compulsory insurance, no-fault or otherwise, and a fund (international) to cover all liability and compensation for damage so that innocent victims of pollution damage can receive adequate reparation.

Another question that the provision does not answer is whether the IMCO Civil Liability Convention (1969) and the International Fund Convention (1971) can be considered as "international law" for the purposes of this provision in the light of the fact that those conventions, if in force, have as parties only a limited number of states. 18/ No attempt will be made here

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17/ See UN Doc. A/CONF.62/WP.8/Rev.1/Part III, op. cit. supra. Also see Note 16 for remarks on status of text.

18/ The Civil Liability Convention came into force on June 19, 1975, and only 14 states are parties to it. The Fund Convention has not yet come into force and effect, and has to date only five parties to it.

to examine the provisions of those conventions. Suffice it to say, however, that the two IMCO Conventions deal narrowly with civil liability and a fund for oil pollution damage, and seek to a large extent to protect the interests of the major ship-owners rather than those of innocent victims of pollution or the integrity of the marine environment.

3. Developing Political Awareness of Marine Pollution Problems

An attempt has been made so far to look at the politics of pollution in the context of current international negotiations on a new law of the sea. It has not been an easy question to deal with. It has, however, been shown that knowledge and information are basic to the understanding of the problem of marine pollution. Despite the urgency of the problem, a large number of governments do not see pollution as a matter of priority. What has to be done is to press governments into taking early and effective action against marine pollution in all its myriad forms. One of the ways and means of doing this is to arouse political awareness by, among other things, informing and stimulating public opinion. How then can this be done? This is indeed a difficult question to answer.

The public can only be aware of the problem if it has adequate knowledge and information about it. To be informed is to be aware. Information must be presented in such a way that it can have an impact on public consciousness and cognizance. Unless the public feels that its life and livelihood are imminently threatened by the gravity of the pollution problem, it would not demand action from governments. The public must be made to see the direct relation between, on the one hand, the release of toxic substances (like DDT) and other industrial effluents and wastes into our streams and rivers, and, on the other, the poisoning of fish and the eventual destruction of all marine life, with all the serious consequences for human survival. This is but one example. Another is the relationship between the release of oil by vessels in the sea and the pollution of beaches resulting in the destruction of the tourist industry, on which so many countries depend, particularly those in the Caribbean, some islands of which rely on tourism for up to 75% of their national income.

People must be given the facts of pollution if they are to be made politically aware of the problems involved. Facts by themselves are not enough. Facts must be presented in such a way as to give the people a clear perception of those facts so that they can see pollution prevention and control as a national priority. Educational programmes would have to be carefully planned and implemented to bring home to the people the message of pollution. A little bit of evangelising will not hurt. It is here that political leaders must take the initiative and, like Prime Minister Trudeau of Canada, make preservation of the marine environment a national objective. Commonwealth Caribbean leaders should be in the vanguard of the fight against marine pollution, because their countries have more to lose from pollution of their air, streams, rivers and seas. Their environment is in most cases their only on-going resource. They do not all have resources of oil, bauxite and natural gas, and even those resources are not inexhaustible. Their fish is a renewable resource which must be protected from pollution, and their skies and beaches, if preserved from contamination, are resources that cannot be exhausted.

An educational programme must be well conceived and comprehensive in its scope. It must seek to develop in individuals good habits and attitudes towards the environment; for example, no random disposal of trash, aluminium cans, etc., and proper sewage and garbage disposal systems. Since most adults may have already developed habits that may be difficult to break at this stage, the programme must be directed primarily at the young. This is not to say that Adult Education Programmes are not to be instituted on the subject of the preservation of the marine environment, as one of the subjects to be taught to adults at day and evening classes on the human environment. The subject of the marine environment should be a compulsory subject on the curriculum at the primary, secondary and post-secondary levels. It must be taught with the help of all the modern teaching aids available Books on the question of marine pollution must be prepared in language simple enough to be understood by children at all levels. It is reported that text-books on the subject have been prepared and are being experimented with in Venezuela with some success. School plays should be put on with pollution as the theme.

The mass media - particularly radio, newspapers, cinema and television - have a role to play in dramatizing the problems of marine pollution and in pinpointing the dangers of interfering with the ecological balance of the environment. The use of the media must be an integral part of any educational programme. A concerted international effort will have to be made to get film producers to produce works that deal with the deleterious and tragic consequences of marine pollution to human life. Instead of producing a film like "Jaws" in which the man-eating shark is gobbling up human beings, it would be nearer the truth to produce a film which shows how Man, the polluter, is destroying "Jaws".

Both the theatre and cinema must be utilized in the campaign against marine pollution. An enlightened public, aware of its responsibility to mankind in perpetuity, must demand of the cinema and theatre, the dramatizing of the pollution problem. This the public can do by withholding its patronage until demands are met. The public cannot wait until real theatre dramatizes the problem for it. It cannot wait until disaster has struck before it demands action of its legislators and decision-makers. It cannot wait, as a tragic hero, until the real-life drama has played itself to a terrifying dénouement. For man, such a tragedy would be catastrophic, with irreversible consequences.

4. Summary and Conclusions

In view of the fact that land, sea and air are integral parts of the same ecosystem, marine pollution problems cannot be dealt with separately from those concerning the land and stmosphere. Man, oblivious of his impact on the environment, has, in his concern with technological advancement and economic development, polluted land, sea and air. The wastes of modern industry have reached alarming proportions. The few kinds of pollution that have actually been measured seem to be increasing "exponentially". There is evidence that man has so degraded the environment that irreversible damage has already been done. Pollution growth must have an upper limit before the disastrous explosion takes place. No-one appears to know where that upper limit is. As a result, man cannot continue to maintain an attitude of

reckless abandon and indifference to the problems of marine pollution in complete disregard for his own health, happiness and survival. Such an attitude is clearly suicidal. Man must therefore set up the control measures necessary to prevent pollution growth from reaching the upper limits and so avert ecological disaster.

The current Law of the Sea negotiations have given new focus and emphasis to the political aspects of marine pollution. Those negotiations have shown the need for more precise knowledge and information about marine pollution so as to enable meaningful and effective decisions to be taken. They have revealed some basic political conflicts between economic development and pollution control and prevention, and between the interests of states and those of the corporate international community. An accommodation of divergent interests must be reached if those conflicts are to be resolved. It is to be hoped, however, that accommodations will not be reached in such a way as to sacrifice environmental interests. In the race by states to grab ocean wealth within and beyond national jurisdiction, it is feared that no proper regard or concern will be shown for the preservation of the marine environment. The need arises therefore for the 156 states at the Third UN Conference on the Law of the Sea to build institutional mechanisms that are strong and comprehensive enough to safeguard and protect the environment from progressively increasing growth of pollution in our seas and oceans.

It is imperative to develop worldwide awareness of the need to minimize pollution in all its forms - to avoid the release of chemical, toxic and other wastes into canals, streams, rivers and the sea; to impose universally high standards for the design, construction, equipment and manning of all vessels; to devise a system to protect special marine areas which are sensitive and fragile, and to ensure that land-based industries meet acceptable environmental standards or not be permitted to operate at all.

States must enact legislation on all aspects of pollution, and impose penalties for offences severe enough to deter prospective offenders. States must also have the political will to enforce its laws in this respect. In order to avoid conflicts in respect of standards laid down for the construction and equipment of ships, states should be required to establish international standards through competent international bodies. Safe construction and discharge standards are prerequisites in any system for protecting the environment. It is to be noted that a structurally unsound tanker can break up and sink, causing in the process irreparable harm to the environment.

It has been evident in the Law of the Sea negotiations that in attempting to strike a balance between the interest of flag states and of coastal states in respect of marine pollution jurisdiction, greater concern has been shown for the protection of the maritime interests of the flag state than with the vested interest of the coastal state in protecting its territory, or with that of the corporate international community in keeping the seas, oceans and coastlines of the world unpolluted.

The marine pollution problem must be treated by states as a matter of urgent priority. Marine scientific research must be undertaken to monitor pollution, to identify and finger-print sources of pollution and to invent

techniques for combatting and eliminating pollution. The seas and oceans must be policed continuously to detect and arrest polluters and to produce evidence for their prosecution. As stated earlier, penalties for offences must be severe, and adequate compensation should be made so that innocent victims of pollution damage can be compensated. Thought should be given to the establishment of compulsory no-fault insurance schemes to cover all pollution damage in civil matters, without affecting, however, criminal sanctions against offenders for negligence or wilful misconduct as a result of acts either of non-feasance, misfeasance or malfeasance. What appears to be required for the seas and oceans are national police "flying squads" trained as crack marine units to deal with marine pollution offences.

The co-operation of states is a necessary ingredient for concerted action in the battle against pollution. Each state should have a national contingency plan to take effective action in cases of oil spills resulting from maritime accidents. Where states share an enclosed or semi-enclosed sea, they must work out together regional contingency plans for such accidents. In the Area beyond national jurisdiction, an International Authority should have jurisdiction over pollution matters, not leaving matters to the laissez-faire jurisdiction of flag states. Flag states must be made to comply with rules laid down internationally and take effective enforcement action against ships flying their flat. The International Authority should, with the co-operation of states and international organizations, work out its own contingency plan to deal with accidents on the high seas, particularly those resulting in serious oil spills.

It is regrettable that the level of political awareness, on the part of states, of marine pollution problems is so low. Once this state of affairs remains, governments will continue to take marine pollution lightly and not consider it as a question requiring priority treatment and attention. It has been extremely difficult to find ways and means to raise the level of political awareness. Some suggestions have been made here, however. They point to the need to mobilize public opinion in the fight against marine pollution so as to create environmental pressure groups that ventilate the issue and force governments to take action. Teaching people to observe good environmental habits, and training employees in good pollution control practices and habits are two elementary methods of attacking the problem. It has been suggested that teaching and indoctrinating the young to respect the human environment is a productive way to develop political awareness of marine pollution problems.

The mass media - particularly radio, television, cinema and newspapers - must be made to play an important role in this process of raising the level of political awareness. Governments must be made by the public to assume their responsibilities in respect of marine pollution. No matter what the level of awareness, enforcement action by governments remains crucial to successful pollution prevention and control.

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